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Abstract: Dynamic dispatch, or late binding of function calls, is a salient feature of object-oriented programming languages like C++ and Java. It can be costly on deeply pipelined processors, because dynamic calls translate to hard to predict multi-way branch instructions, which are prone to causing pipeline bubbles. Several alternative implementation techniques have been designed in the past in order to perform dynamic dispatch without relying on these expensive branch instructions. Unfortunately it is difficult to compare the performance of these competing techniques, and the issue of which technique is best under what conditions still has no clear answer. In this study we aim to answer this question, by measuring the performance of four alternative control structures for dynamic dispatch on several execution environments, under a variety of precisely controlled execution conditions.

Key-words: Java, dynamic dispatch, control structure, optimization, JVM

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Evaluation des Structures de Contrôle pour la Liaison Dynamique en Java

Résumé : La liaison dynamique, ou envoi de messages, est un concept saillant dans les langages à objets comme C++ et Java. Ce concept peut être coûteux sur des processeurs ayant un profond pipeline car les appels dynamiques résultent en des instructions de branchements multiples difficiles à prédire, prompts à causer des bulles dans le pipeline. Diverses techniques d'implantation alternatives ont été proposées dans le passé pour faire la liaison dynamique sans se baser sur ces coûteuses instructions de branchement. Malheureusement, il est difficile de comparer les performances de ces techniques compétitives et trouver laquelle est la meilleure sous quelles conditions n'a toujours pas de réponse claire. Dans cette étude, nous cherchons à répondre à cette question, en mesurant les performances de quatre structures de contrôle alternatives pour la liaison dynamique, au sein de plusieurs environnements d'exécution et sous diverses conditions d'exécution précisément contrôlées.

Mots-clés : Java, liaison dynamique, structures de contrôle, optimisation, JVM

Evaluation of Control Structures for Dynamic Dispatch in Java

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1 Introduction

Object-oriented message dispatch is a language feature that enables data — objects — to provide a general functionality — message — by relying on a type-specific implementation, or method. At run time, the object that receives a message, or virtual method call, retrieves the corresponding class-specific method and invokes it. This late binding of dispatch targets allows any object to play the role of the receiver object, as long as the new object implements the expected interface (is substitutable à la Liskov [19]). Such type-substitutability enables code abstraction and code re-use, and is therefore one of the main advantages of object-oriented languages.

As a consequence, dynamic dispatch occurs frequently in object-oriented programs. For instance, virtual method invocations in Java [14] occur every 12 to 40 byte codes [11] in SPEC JVM98. Such lately-bound calls are typically expensive on modern deeply pipelined processors, because they translate to hard to predict multi-way branch instructions, which are a cause for long pipeline bubbles. Dynamic dispatch thus has to be optimized, in order

*Karel Driesen est professeur à McGill University, Montréal, Canada to avoid incurring a significant performance penalty when relying on the object-oriented design style.

Alternative implementation techniques are available to perform dispatch to multiple targets without using expensive branch instructions. Unfortunately, comparing the performance of these competitive techniques is hard, and the literature typically reports measurements of few alternatives, on only one execution environment.

In this study, we propose and report on the results of a methodology to measure the performance of several control structures for dynamic dispatch on a *variety of Java Virtual Machines and hardware platforms.* We rely on micro-kernel benchmarking to determine the relative performance of control instructions under a large number of *varying execution conditions.*

The results show, among other things, that:

- Virtual method call performance is highly *dependent on the execution pattern* at a particular call site
- When the call site has a low to medium degree of polymorphism (2-3 target types up to 6-8 target types), optimizations are possible that *improve performance across JVMs and hardware platforms* (platform independent optimization)
- *Processor architecture shines through*, especially on high-performance JVMs: the performance profile from different VMs executing on the same hardware look similar, those from the same VM executing on different hardware look different.

This paper is organized as follows. Section 2 reviews dynamic dispatch implementations and related work at software, run-time system and hardware level. Section 3 presents our methodology and the experimental setup. Section 4 presents some of our results and discusses them. Finally, section 5 concludes and points at future research directions.

2 Background

2.1 Monomorphism vs. Polymorphism

Dynamic dispatch is expensive because the target method depends on the run-time type of the receiver, which generally cannot be determined until actual execution.

Many different optimization techniques have thus been proposed, which can be seen as falling into two broad categories:

Optimizing monomorphic calls Dynamic dispatch being expensive, the fastest way to do it is to avoid it altogether.

Various kinds of *program type analysis* (e.g. [6, 20, 21]) enable the de-virtualization of provably monomorphic calls (calls with only one target type), replacing the expensive lately-bound call by by a direct, cheaper, early-bound call. This technique has the added advantage of allowing inlining of target methods, thus stripping away all of the call overhead and enabling a more radical optimization of the inlined code by classical methods.

Dynamic optimization (e.g [5, 16]) such as employed by the SUN HotSpot™ Server JVM allows method inlining at run time, which permits further optimization of calls that are monomorphic in only a particular run of the program, even though multiple target types are possible after compile time.

Optimizing polymorphic calls Despite all efforts, some calls cannot be resolved as monomorphic. Optimizing the remaining polymorphic ones (calls with more than one target type) is crucial.

Program type analysis can also optimize these polymorphic calls, especially when the number of possible types is very low. For example, a compiler can replace a lately-bound call with two possible target types by a conditional branch and two static, direct, early-bound calls. At run time, a cheap conditional branch and cheap static call are executed instead of one expensive lately-bound call (strength reduction). Such a strength reduction operation is usually a win on current processors. Furthermore, the most dominant call direction can be inlined, leading to similar optimization opportunities as for monomorphic calls, with the guard of a cheap conditional branch [1].

Dynamic optimization can also replace a call that is dominated by one target type at run time, enabling the same operation as above with increased type precision.

These solutions to optimize dynamic dispatch are amenable to two approaches: hardware and software.

2.2 Hardware Solutions

Virtual method invocations in Java translate, in the native code, into two dependent loads followed by an *indirect branch*. The latter is responsible for most of the call overhead [8]. Branches are expensive on modern, deeply pipelined processors because the next instruction cannot be fetched with certainty until the branch is resolved, typically at a late stage in the pipeline (e.g. after 10-20 cycles on a Pentium III).

Most processors try to avoid these pipeline bubbles by speculatively executing instructions of the most likely execution path, as predicted by separate *branch prediction* micro-architectures. For example, a Branch Target Buffer (BTB) stores one target for each multi-way branch and can predict monomorphic branches with close to 100% accuracy, which removes the branch misprediction overhead.

Unfortunately, polymorphic calls are harder to predict. Sophisticated two-level indirect branch predictors [4] can provide a similar advantage as a BTB for multi-target indirect branches that are "regular" and whose target correlates with the past history of executed branches.

Unfortunately, indirect branches are more difficult to predict than conditional branches. A conditional branch has only one target, encoded in the instruction itself as an offset, so a processor only needs to predict whether the conditional branch is taken or not (one bit). Indirect branches can have many different targets and therefore require prediction of the complete target address (32 or 64 bits). Sophisticated predictors [9, 10] can reach high prediction rates, but generally require large on-chip structures. Indirect branch predictors thus tend to be more costly and in practice less accurate than conditional branch predictors (Branch History Buffers, BHTs), even in modern processors.

Therefore, replacing an unpredictable indirect, multi-way branch by one or several more predictable conditional branches followed by a static call seems a likely optimization. This strength reduction of control structures is exploited by several of the techniques in the next section.

2.3 Software Solutions

Most JVMs include some way to de-virtualize method invocations which are actually monomorphic, by replacing the costly polymorphic call sequence by a direct jump. For example, various forms of whole program analysis (e.g. [2, 21]) show that most invocations in Java are monomorphic.

Some JVMs use a dynamic approach, like HotSpot, which relies on a form of inline caching [7, 22]. The first time a virtual method invocation is executed, it is replaced by a direct call preceded by a type check. Subsequent executions with the same target are thus direct, whereas executions with a different target fall back to a standard virtual function call.

Actual run-time polymorphism can also be optimized in software, for example by using Binary Tree Dispatch (BTD), as implemented in SmallEiffel [25]. BTD replaces a sequence of powerful dispatch instructions using an indirect branch by a sequence of simpler instructions (conditional branches and direct calls). When the sequence of simple instructions remains small, it can be more efficient than a call through a virtual function table, and should perform particularly well on processors with accurate conditional branch prediction and large BHT. A BTD is a static version of what is commonly known as a Polymorphic Inline Cache [15]. A PIC collects targets dynamically at run time (it is a restricted form of self-modifying code), effectively translating a lengthy method lookup process into a sequential search through a small number of targets. The *if sequence* control structure exercised in our micro benchmark suite (see section 3.3) is akin to the implementation of a PIC described in [15]. As in the latter paper, we found that megamorphic call sites (more than 10 possible target types) are too large for a sequential *if* to be cost-effective.

Chambers and Chen also proposed a hybrid implementation mechanism [3] for dynamic dispatch that chooses between alternative implementations of virtual calls based on various heuristics. The experiments in our study complement their approach, since we aim to more precisely define the gains and cutoff points reachable with each technique on multiple platforms.

3 Methodology

3.1 Overview

We started this work in order to find out whether control structure strength reduction could be used to optimize dynamic dispatch under specific execution conditions and across different hardware platforms, i.e. to find out whether platform-independent optimization is feasible.

In order to allow platform-independent optimization to be effective, two conditions must hold. First, strength-reducing operations must be guided by platform-independent information; the analysis may include profile data if it is not platform-specific. Second, the performance of control structures must be consistent across platforms.

The first condition is fulfilled by various forms of static program analysis and program-level profiling, and many studies show that optimizable call sites are common.

The second condition needs to be verified. Even the reasonable assumption that direct static calls are faster than monomorphic virtual ones may not always hold in practice due to implementation features, at the virtual machine level or at the processor micro-architecture level. For instance, a Pentium III stores the most recent target of indirect branches, which can make monomorphic virtual calls as efficient as static calls. In the next section we discuss our experimental framework to measure performance of control structures across different JVM and hardware platforms.

3.2 Experimental Setup

Since we focus on polymorphic calls, a large variety of execution behaviors and control structures has to be measured on several platforms. Therefore, we design a comprehensive suite of Java micro benchmarks to test the performance of control structures under controlled execution conditions, leveraging the wide availability of the Java VM to measure on different execution environments.

All benchmarks use the same superstructure: a long-running loop that calls a static routine which performs the measured dispatch. The receiver object (actually, its type ID) is retrieved from a large array, which is initialized from a file that stores a particular execution pattern as a sequence of type IDs. This initialization process ensures that compile-time prediction of the type pattern is impossible. Different files store a variety of type ID sequences, representing different patterns and degrees of polymorphism.

The experimental parameter space thus varies along three dimensions:

Control structures How do different different control structures for dynamic dispatch perform?

Execution patterns This dimension has three related sub-dimensions. First, the *static number* of possible receiver types at the dispatch site, which influences the program code and can be determined by program analysis before execution. Second, the *dynamic number* of receiver types at the dispatch site, that is the range of types occurring in a particular program run. Third, the *pattern* of receiver type IDs, that is the order and variability of receiver types at run time.

Execution environments This dimension has two related sub-dimensions: the *virtual machine* used and the *processor* it is run on.

Each data point (timing) within this parameter space is measured as follows. First, the benchmark is run 5 times on a long (10M) loop, which gives a "long run average" running time. The latter comprises only the loop part (not the initialization). When executed on dynamically optimizing JVMs such as HotSpot, this execution time comprises both the execution as "cold code" and the execution as optimized once the optimizer has determined the loop is a "hot" one. The JVM is thus given ample opportunity to fully optimize control structures. Then, the benchmark is re-run 5 times on a very long (60M) loop, which provides a "very long run average". The difference between these two averages, "long" and "very long", represents only "hot", optimized loops, and gives us our final result after normalization to 10M loops.

The three dimensions of the parameter space are detailed in sections 3.3, 3.4 and 3.5.

3.3 Various control structures

We measure a variety of control structures for dynamic dispatch implementation. Although it is not comprehensive, we believe it covers the main possibilities available to optimizing compilers at the bytecode and native code level.

Virtual calls At the Java source code level, a dispatch site is a simple method call: `x.foo()`. At the Java bytecode level, a special instruction is provided to implement virtual calls: `invokevirtual`. The dynamic dispatch instruction uses the message signature (argument to the `invokevirtual` bytecode) and the dynamic type of the receiver object (atop the stack) to determine the actual target method. Generally, this translates at the hardware level into a table-based indirect call [12]. This constitutes the first implementation of dynamic dispatch we tested, in our "Virtual" series of micro-benchmarks.

It is however possible to use other control structures, based on simpler bytecode instructions, such as type equality tests followed by static calls. These control structures can take at least three forms:

If sequence First, a sequence of 2-way conditional type checks can be used. For example, let's assume a polymorphic site `x.foo()` where global analysis detected the receiver could only have four possible concrete types at runtime: T_A, T_B, T_C and T_D. The corresponding pseudo-code is shown in figure 1. This implementation of dynamic dispatch is tested in our "IfSequence" series of micro-benchmarks, where the type ID is an integer stored in an extra field of every object.

```
localTypeID = x.typeID;
if (localTypeID == ID_FOR_TYPE_A) then
    foo_A(x);
else if (localTypeID == ID_FOR_TYPE_B) then
    foo_B(x);
else if (localTypeID == ID_FOR_TYPE_C) then
    foo_C(x);
else if (localTypeID == ID_FOR_TYPE_D) then
    foo_D(x);
endif
```

Figure 1: Pseudo-code for if-sequence dispatch

Binary Tree Such 2-way conditional tests can be organized more efficiently, as a binary decision tree [25]. Let's assume the type IDs corresponding to the types T_A, T_B, T_C and T_D, are, respectively, 19, 12, 27 and 15. Then, the pseudo-code generated for `x.foo()` looks like the one in figure 2. We test this implementation of dynamic dispatch in our "BinaryTree" series of micro-benchmarks.

```
localTYpeID = x.typeID;
if (localTypeID <= 15) then
    if (localTypeID <= 12) then
        foo_B(x);
    else
        foo_D(x);
    endif
else
    if (localTypeID <= 19) then
        foo_A(x);
    else
        foo_C(x);
    endif
endif
```

Figure 2: Pseudo-code for binary tree dispatch

Switch Finally, a multi-way conditional instruction can be used, namely a Java dense `switch`, translated into a `tableswitch` bytecode instruction, whose suggested implementation [18] by the JVM is an indirection in a table[1]. The corresponding pseudo-code, tested in our "Switch" series of micro-benchmarks, is shown in figure 3.

```
localTYpeID = x.typeID;
switch (localTYpeID)
    case ID_FOR_TYPE_A then
        foo_A(x);
    case ID_FOR_TYPE_B then
        foo_B(x);
    case ID_FOR_TYPE_C then
        foo_C(x);
    else ID_FOR_TYPE_D then
        foo_D(x);
endswitch
```

Figure 3: Pseudo-code for tableswitch dispatch

The general idea behind strength reduction for dynamic dispatch is that simpler instructions, although more numerous, should be more predictable and executed faster than complex instructions.

All these control structures, except the plain `invokevirtual`, have a size that is proportional to the number of tested types. When used to implement dynamic dispatch, without any fall-back technique, all possible types have to be tested; this set of possible types thus has to be determined by a global analysis. This is accounted for in our benchmark suite, by creating, for each distinct dispatch technique, several benchmarks differing only by the number of types they can handle.

In the latter three control structures, the `foo_X(x)` leaf calls are purely monomorphic. They are implemented as Java static calls, with the original receiver object being passed as the first argument (instead of being the implicit `this` argument in the virtual call)[2]. We thus gave a "StaticThisarg" suffix to these benchmarks.

Note that these last 3 techniques may also be used to serve as run-time adaptive caches catching the most frequent or more recent types, preceding a more general fall-back technique. In this case, they would be akin to PICs, or more accurately, as different alternative control structures which can be used to implement various sizes of PICs.

[1] For the sake of simplicity, we only test dense switches. Sparse ones should be translated into a `lookupswitch` bytecode instruction, that can be implemented by the JVM as a series of ifs or a binary search.

[2] We also test leaves implemented as monomorphic virtual calls which, as expected, turn out to be generally slower than the static leaves.

3.4 Various type patterns

The runtime behavior of the program is another crucial factor in the performance of a given dynamic dispatch site. In order to simulate varying behaviors while keeping precise control, we timed our benchmarks by generating various type ID patterns. Each micro benchmark reads a particular pattern from file at run time to initialize a 10K int array holding type IDs, which is then iterated over a large number of times.

For this study, we used synthetic patterns which represent extremes in program behavior. We plan to use real applications or real application traces in future work. The following four patterns are presented below and in figure 4: the constant pattern, the random pattern, the cyclic pattern and the stepped pattern.

Constant This pattern is the 100% monomorphic case, where the receiver type is always the same, and is thus perfectly predictable. This is a very common case. Various techniques detect such monomorphic dispatch sites and get rid of them by replacing them with direct calls (de-virtualization). However, these techniques may not always be applied, do not detect all monomorphic call sites and do not handle call sites that are in principle polymorphic but never change targets within any single run. It is thus worth testing the behavior of dynamic dispatch techniques on this best-case constant pattern. Since the value of the constant type ID influences performance, we test various IDs within the static range.

Random This pattern is the exact opposite of the previous one: it can't be predicted, features high polymorphism (many receiver types) and high variability (many changes during execution). As such, it represents a worst-case scenario likely to be rare in object-oriented programs.

Cyclic The cyclic pattern features a regular variation of the type ID, each ID being the previous one incremented by 1 up to maxID and back to 1, and so on. This pattern is thus highly polymorphic and has a very high variability (the type changes at every call), like the random pattern, but is still very regular. Advanced micro-architecture such as two-level branch predictors are capable of detecting some cyclic branch behavior and therefore should predict this pattern accurately, especially for small cycles. As such, and even though it is probably fairly uncommon in OO programs, this pattern represents a kind of intermediate point between constant and random.

Stepped This pattern is a regular variation of the cyclic pattern, close to the constant pattern in behavior. It features a variation of the type ID for 1 to maxID, with increments of 1, but with as few changes as possible within a single run. It thus exhibits long, constant steps, whereas the cyclic pattern has a step length of 1. The stepped pattern has the same degree of polymorphism as the cyclic one (same number of types), but much lower variability. It should thus be highly predictable, even by simple predictors such as a Branch Target Buffer. This stepped pattern is probably quite common in OO programs, for example when iterating over containers of objects, which often contain instances of a single type.

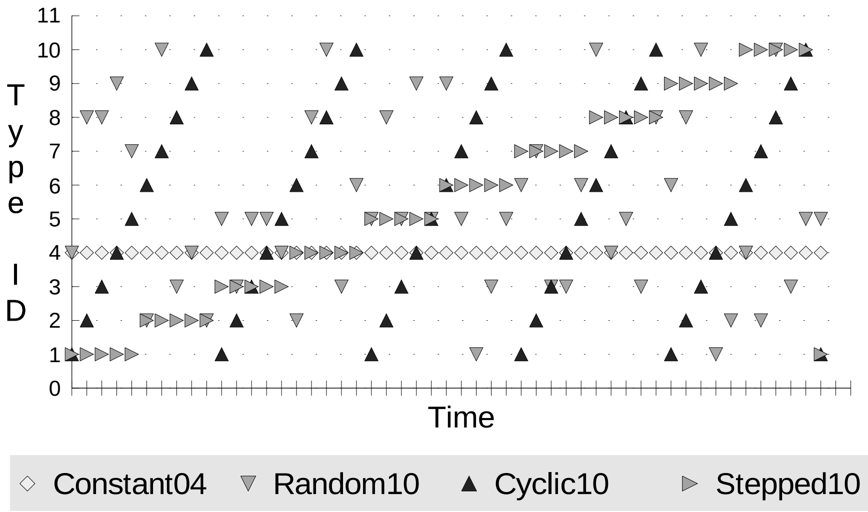

Figure 4: Patterns dynamic behavior

3.5 Various execution environments

Execution environment, the last varying dimension in our study, consists of two parts: the hardware platform and the virtual machine used to execute the benchmarks. Running different virtual machines is similar to testing a particular program using different compilers. The addition of an extra execution layer, the JVM, makes execution more complex and makes it significantly harder to interpret performance results, but it provides platform-independence and is thus essential to our approach.

The benchmark suite was run on four hardware platforms[3]:

SUN UltraSparc III This machine features one 750MHz processor and 1GB of RAM, with SunOS 5.8.

Intel Pentium III This machine has dual 733MHz processors, with 512MB of RAM, running Linux Mandrake with kernel 2.2.19. Note that for our benchmarks, dual processor capability should have little if no impact.

Intel Celeron This low-end machine comprises one 466MHz Celeron with 192 MB of RAM and Linux Mandrake with kernel 2.2.17.

AMD Athlon This machine features one 1.4GHz Athlon processor, with 1GB of RAM and Linux Mandrake with kernel 2.4.3.

[3]For space reasons we show results for two platforms only.

Of course, not all JVMs are available on all hardware platforms. Furthermore, the fact that a JVM is available under the same name on two different hardware platforms is no guarantee at all they are indeed the same JVM: their back-ends for instance must be different. The JVMs tested during this study are generally in their 1.3.1 version. We show the IBM JVM (known as "the Tokyo JIT") and the SUN HotSpot Server as examples of high-performance JVMs and the SUN HotSpot Client, which is the most widely available JVM, and runs on many different hardware platforms.

The following result section shows the essence of the large amount of data gathered.

4 Results and discussion

As explained in the previous section, we measure the performance of different control structures in a number of varying dimensions: hardware, JVM, number of possible types (static) and type pattern (dynamic). This leads to a vast parameter space, in which we gather a large number of data points (more than 21,000).

For space constraints reasons, we cannot show all the data and therefore we pick a representative sample: the dual Pentium III and the UltraSparc III, two hardware platforms described in section 3.5. We also focus on a maximum number of possible types (static) of 20, which allows testing both low and high degrees of polymorphism, with patterns featuring as low as 1 actual live type at runtime (monomorphic) and as many as 20 (megamorphic [1]). Overall, this maximum degree of polymorphism of 20 is representative of behaviors and data we gathered at various sizes[4]. Shorter static type sizes typically lead to more efficient *if sequences* and binary search trees.

Results are presented in figures 5 and 6, that show two different JVMs on the same Pentium platform, as well as in figures 7 and 8 that show the HotSpot client JVM on two different hardware platforms.

On all these graphs, the same 5 benchmarks are tested, resulting in the 5 curves on each graph:

Virtual20 A plain virtual call (`invokevirtual`) that can cope with any number of possible receiver types[5].

BinaryTreeStaticThisarg20 A binary tree dispatch, with 20 leaves that are static calls, the receiver object being passed as an explicit argument.

IfSequenceStaticThisarg20 A sequence of ifs, with 20 static leaf calls.

SwitchStaticThisarg20 A Java switch, translated into a `tableswitch` bytecode with 20 cases, each being a static call.

[4] We actually tested all maximum sizes from 1 to 10, then 20, 30, 50 and 90.

[5] For Virtual and NoCall, the "20" in the name is only kept for consistency with other benchmark names.

NoCall20 This benchmark contains no call at all, it shows the base cost of the benchmark mechanism (loop and static method call)[6].

The different control structures are tested against 41 execution patterns of the four kinds presented in section 3.4, constant, cyclic, random and stepped, that compose the x axis. The numbers appearing in the pattern name indicate the active range of type IDs for each pattern. Thus `rnd-01-07` is a pattern made of random type IDs between 1 and 7, `step-01-09` is a type ID pattern with 9 steps, from 1 to 9, and `cst-04` is a pattern with constant type ID 4, and so on.

4.1 Observations

Figure 5 shows performance in milliseconds of execution time for the IBM JIT on a Pentium III. Plain *virtual calls* (`invokevirtual`, shown as continuous black curve) appear to be sensitive to the dynamic execution patterns tested. Virtual calls executing constant patterns and stepped patterns take about 700 ms, compared to 1000 ms for cyclic and random patterns. The NoCall20 micro-benchmark executes in 600 ms. Therefore the overhead of virtual calls varies between 100 and 400 ms, a factor of four due only to differences in type patterns. Other JVMs on the Pentium platform show similar ratios (figures 5 and 6). On an UltraSparc III (figure 8), virtual calls appear less sensitive to execution patterns. The constant pattern is executed slightly more efficiently, but a stepped pattern shows the same performance as a random or cyclic pattern. In contrast, stepped patterns with low variability behave well on all Pentium JVMs (figures 5, 6 and 7), with a cost close to that of the constant pattern. Overall, virtual calls tend to be more expensive than other structures especially when the number of different types is small and when the type pattern is cyclic. These results indicate optimization opportunities for JVM implementors.

The performance of *if sequences* depends on the size of the sequence and the rank of ifs exercised, shorter sequences being faster. Short *if sequences* are the most efficient way to implement dynamic dispatch among the tested control structures across all platforms, all JVMs and all execution patterns. Although the precise cutoff point varies, it is safe to consider that *if sequences* up to 4 are a sure win over current implementations of virtual calls. The actual gain in performance varies but can be as high as 52% (including benchmark overhead) on the duomorphic `cycl-01-02` pattern on HotSpot Server on Pentium III (figure 6) or 24% on the `step-01-02` pattern on HotSpot Client on UltraSparc III (figure 8). Therefore one can significantly optimize the implementation of dynamic dispatch in current JVMs when the number of possible types is known (by static analysis or dynamic sampling) to be small.

Binary tree dispatch (BTD) provides another way to perform strength reduction of dynamic dispatch sites. Binary trees appear to be significantly faster than virtual calls in most cases (all figures, particularly figures 6 and 8). When BTDs are slower than virtual calls,

[6]The "Infinite..." results in figure 6 correspond to executions of NoCall20 that never completed. This reproducible problem occurs only within the same execution environment. The micro-benchmark code is correct since the other two JVMs execute NoCall20 predictably without any problem.

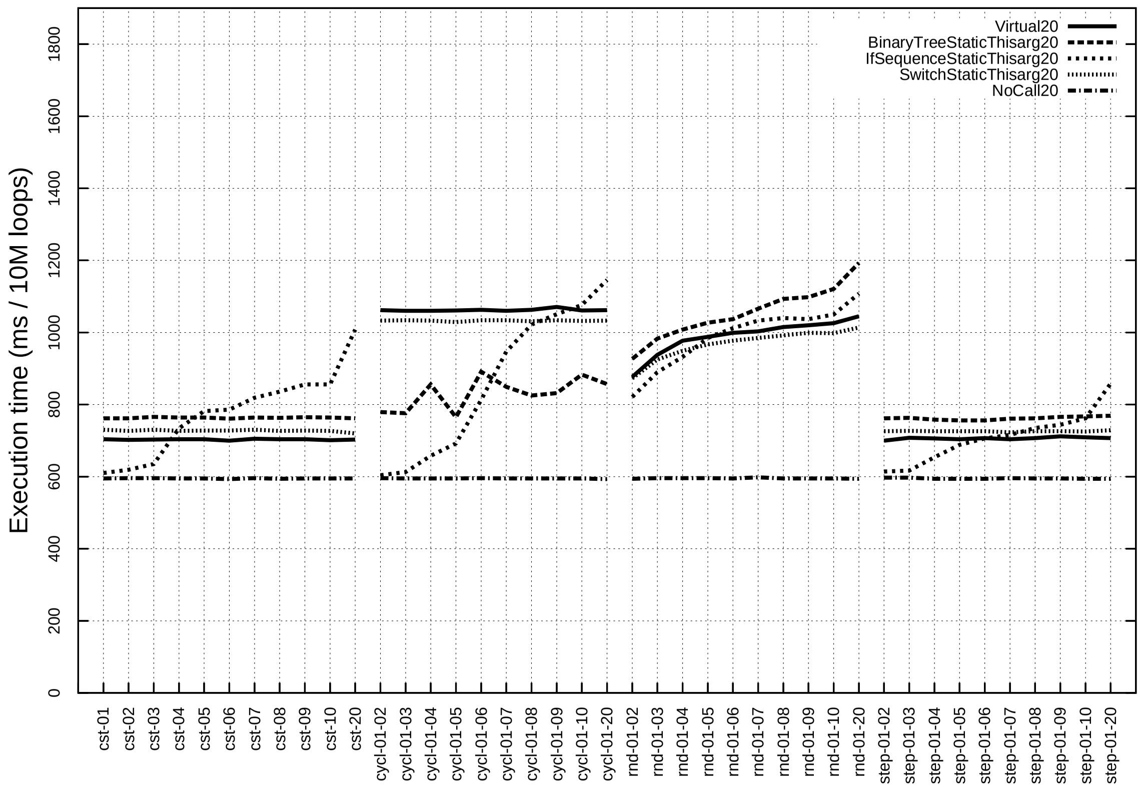

Figure 5: IBM cx130-20010502 on a dual Pentium III

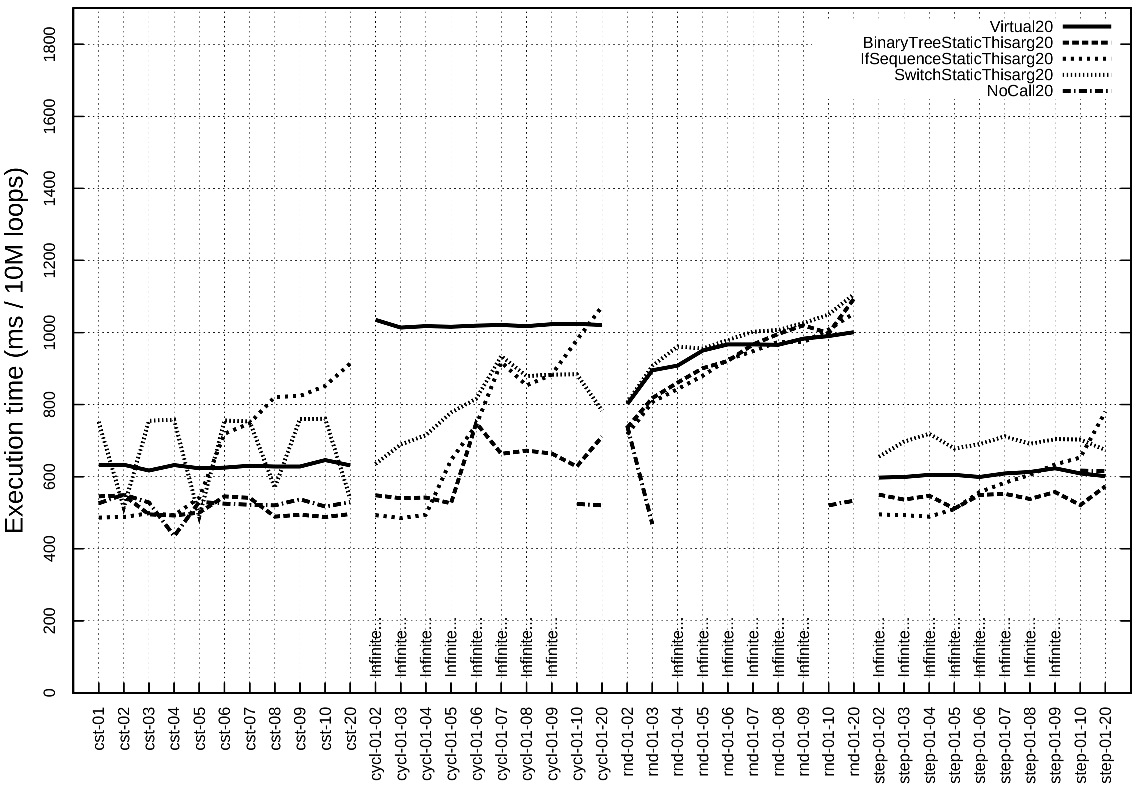

Figure 6: SUN HotSpot Server 1.3.1-b24 on a dual Pentium III

it is generally by a small margin, as figures 5 and 7 show. Since the cost of BTD grows as the logarithm of the number of branches, whereas sequences of *ifs* have a linear cost, BTD is more scalable. This makes BTD a good implementation for dynamic dispatch when the number of types is too large to use simple *if sequences* (above 4 or 8, depending on the JVM and platform), but small enough to prevent extensive code expansion. The cutoff point where BTD become faster than *if sequences* is clearly visible for cyclic patterns on all JVMs and platform, and for constant and stepped patterns in the SUN HotSpot JVMs on both platforms (figures 6, 7 and 8).

Figure 5 shows that Java *dense switches* (`tableswitch`es), when used to implement dynamic dispatch, result in performance very similar to that of virtual calls on the IBM JVM, revealing an implementation based on jump tables. In the HotSpot Client JVM however, both on Pentium III and UltraSparc III (figures 7 and 8), `tableswitch`es behave exactly like *if sequences*, which indicates an actual implementation based on sequences of conditional branches. Table switches are therefore unreliable in terms of performance across JVMs.

4.2 Discussion

We believe that the previous results are important and can be widely used.

First, these results are important to Java compiler and Java VM designers, when implementing multiple-target control structures such as dynamic dispatch. We show that the performance of dynamic dispatch varies a lot across JVMs, hardware and execution patterns. It is safe to say that dynamic dispatch implementation in current JVMs is not always optimal and can be significantly improved, using mostly known techniques. Direct implementation in the virtual machine is likely to provide the highest payoff.

Second, these results are also useful to Java developers, since they stress differences between the various JVMs, highlighting strengths to take advantage of and weaknesses to avoid, such as large `tableswitch`es in the HotSpot Client.

Third, our results show that strength reduction of control structures is likely to be beneficial regardless of the hardware and JVM, when the number of possible receiver types can be determined to be small. For numbers of possible types up to 4, *if sequences* are most efficient. Between 4 and 10, binary tree dispatch is generally preferable. For more types, the best implementation is a classical table-based implementation such as currently provided by most JVMs for virtual calls. These are safe, conservative bets, that generally provide a significant improvement and, when not optimal, result only in a small decrease in performance.

Finally, these measurements expose architectural features (especially branch predictors) of the target hardware. For instance, when executing virtual calls the Pentium III branch target buffer ensures that constant patterns have performance nearly identical to that of slowly changing stepped patterns, whereas this is not the case for the UltraSparc III. Similarly, when executing *if sequences*, small cyclic patterns are predicted accurately by the Pentium's conditional branch predictor, which, for all JVMs, results in better performance on small cyclic patterns than on random patterns.

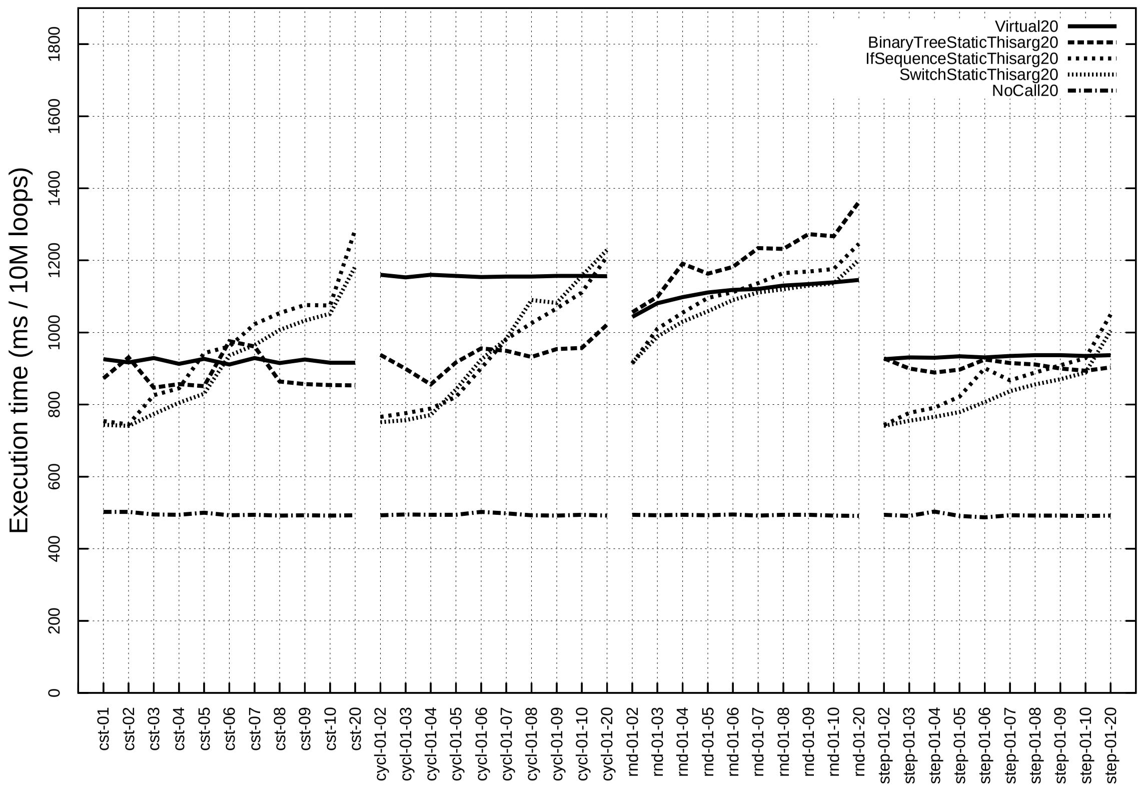

Figure 7: SUN HotSpot Client 1.3.1-b24 on a dual Pentium III

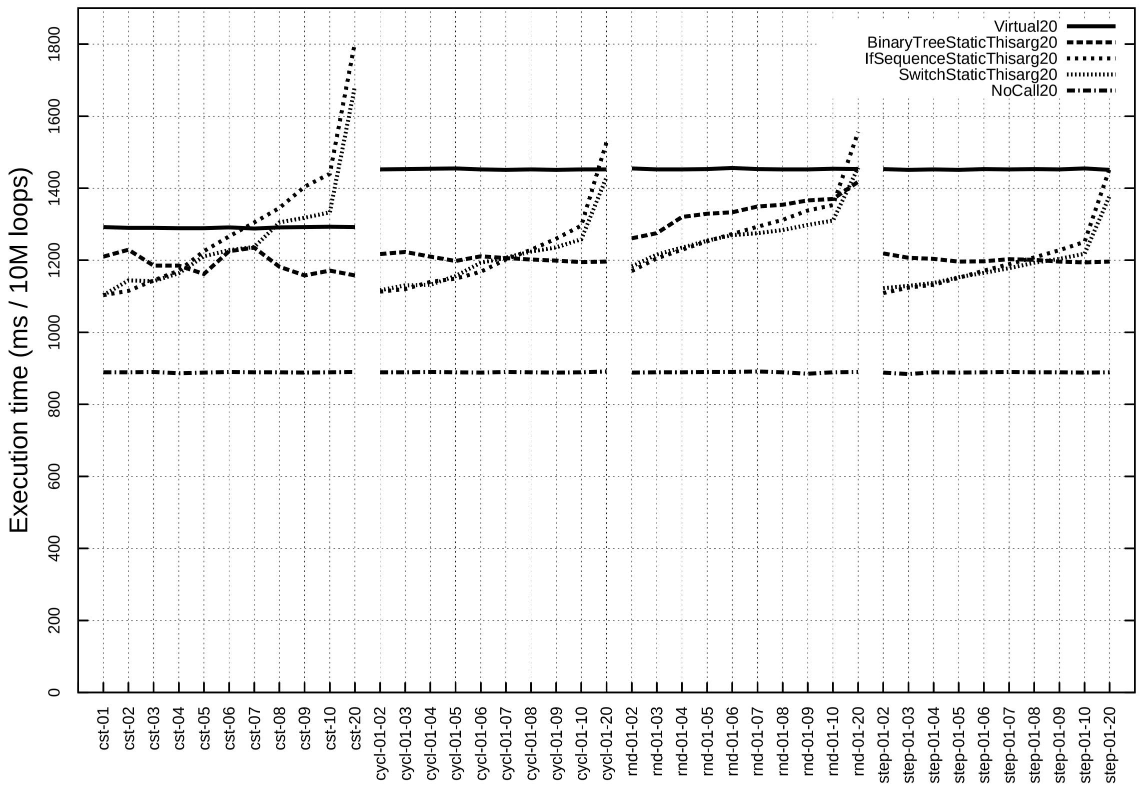

Figure 8: SUN HotSpot Client 1.3.1-b24 on UltraSparc III

Consequently, the results we provide in this paper can be applied at various levels.

They can be used by a static compiler (e.g. javac) that performs a static analysis of the program to determine at compile time the number of possible types, and generate bytecode relying on the most appropriate implementations of dynamic dispatch for each call site, either aggressively targeting a particular platform or conservatively performing transformations for multiple platforms.

JVM implementers can also make use of this information by dynamically compiling bytecode into the most suitable native code structures, based on program execution statistics.

Finally, micro-architecture designers can use these measurements to determine how to support JVMs execution, in particular dynamic dispatch, for instance by providing improved branch prediction mechanisms.

5 Conclusions and future work

The implementation of dynamic dispatch is important for object-oriented program performance. A number of optimization techniques exist, aimed at de-virtualizing polymorphic calls which can be determined, either at compile-time or runtime, to be actually monomorphic. Complementary techniques, either software- or hardware-based, seek to optimize actual run-time polymorphism as well.

We present a study of various control flow structures for dynamic dispatch in Java, with varying hardware, virtual machine and execution patterns.

Our results show that:

- Virtual call performance is highly dependent on the execution pattern at a particular call site.
- When the call site has a low or medium degree of polymorphism (2-3 target types up to about 10), strength reduction of control structures is likely to improve performance across platforms, using *if sequences* for up to 4 different target types and Binary Tree Dispatch between 4 and 10 different types.
- Processor architecture shines through, especially on high-performance JVMs: virtual call performance of stepped patterns, for example, is markedly different on different platforms, but does not vary across different JVMs on the same platform.

In future work, we plan to more precisely assess the efficiency of the techniques we described by directly applying our results to open-source bytecode optimizers, such as Soot [23], or directly in Java Virtual Machines, like the Open VM [24], the Jikes Research VM [17] (formerly Jalapeño) or the SableVM [13].

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A All aggregated graphs for static size 3

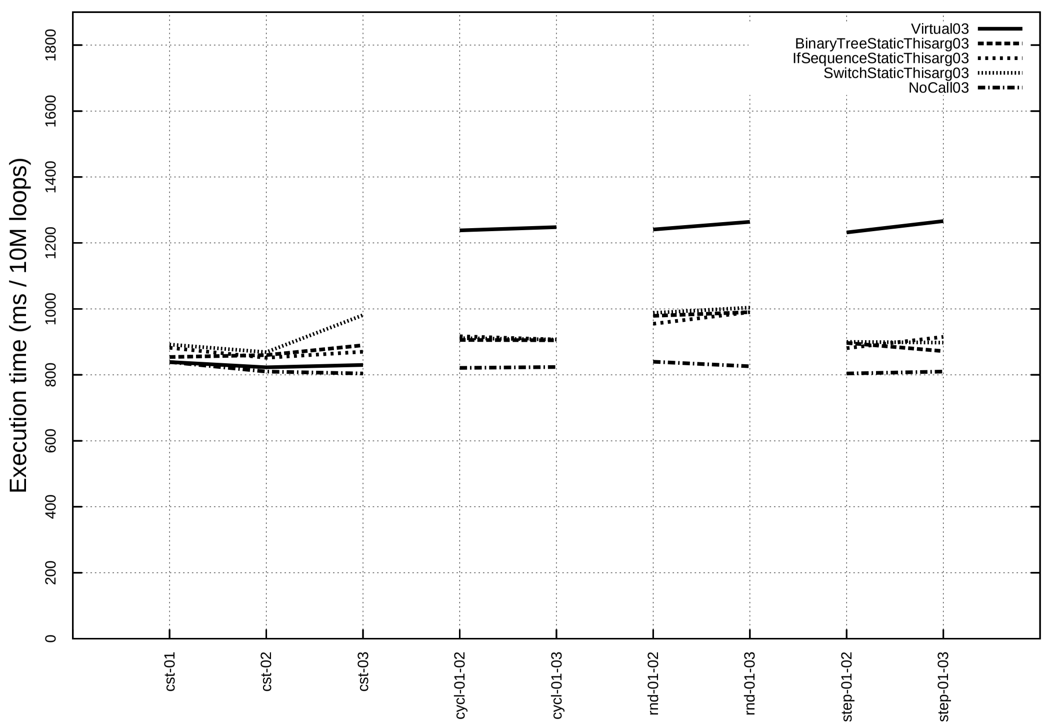


Figure 9: SUN HotSpot Server 1.3.1-b24 on an UltraSparc III 750

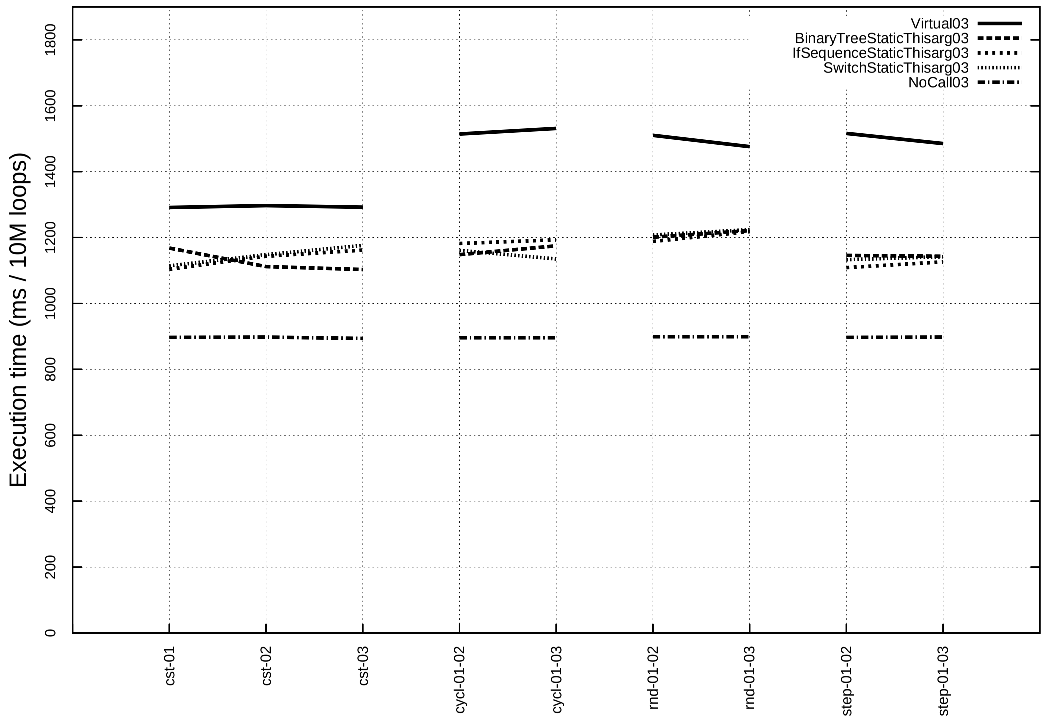


Figure 10: SUN HotSpot Client 1.3.1-b24 on an UltraSparc III 750

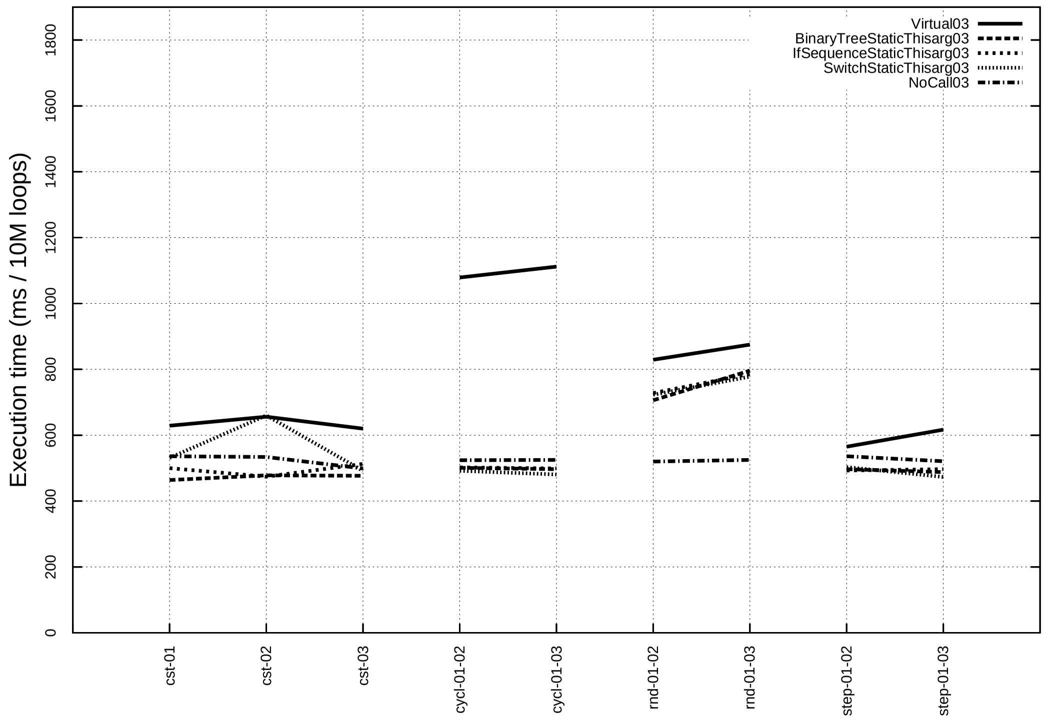


Figure 11: SUN HotSpot Server 1.3.1-b24 on a Dual Pentium III 733

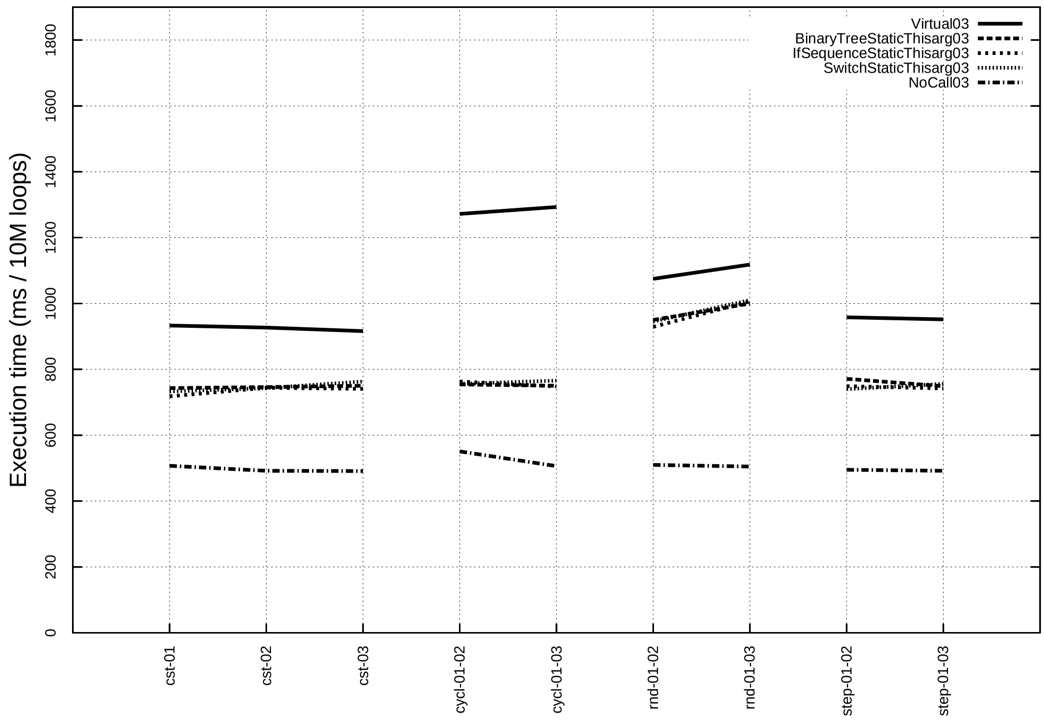


Figure 12: SUN HotSpot Client 1.3.1-b24 on a Dual Pentium III 733

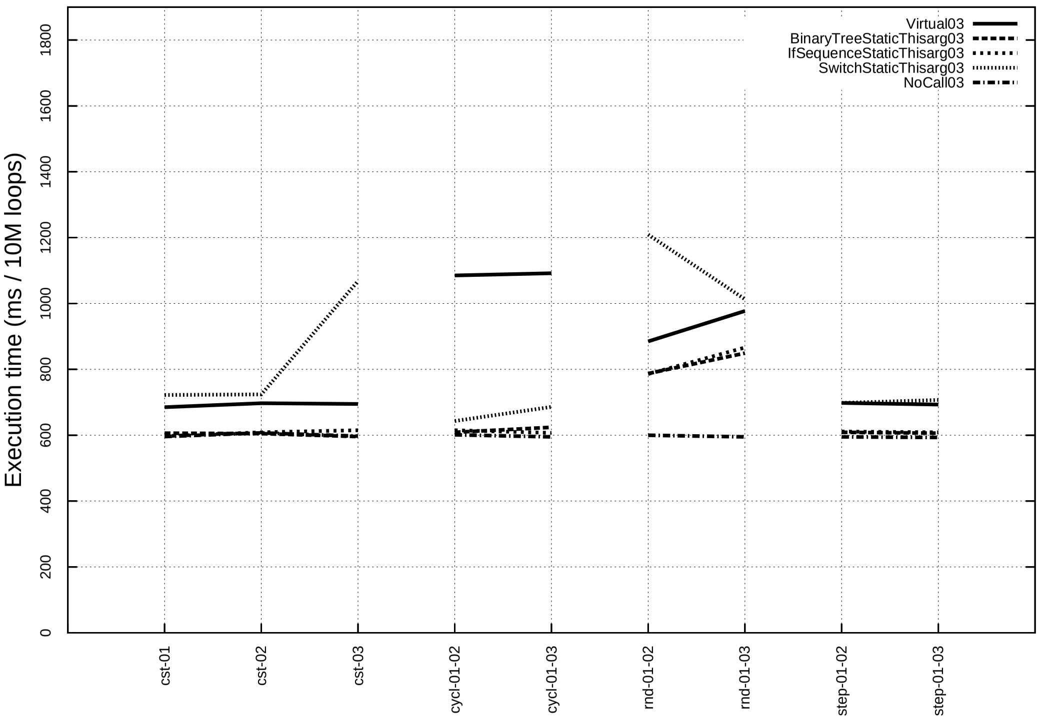


Figure 13: IBM JIT cx130-20010502 on a Dual Pentium III 733

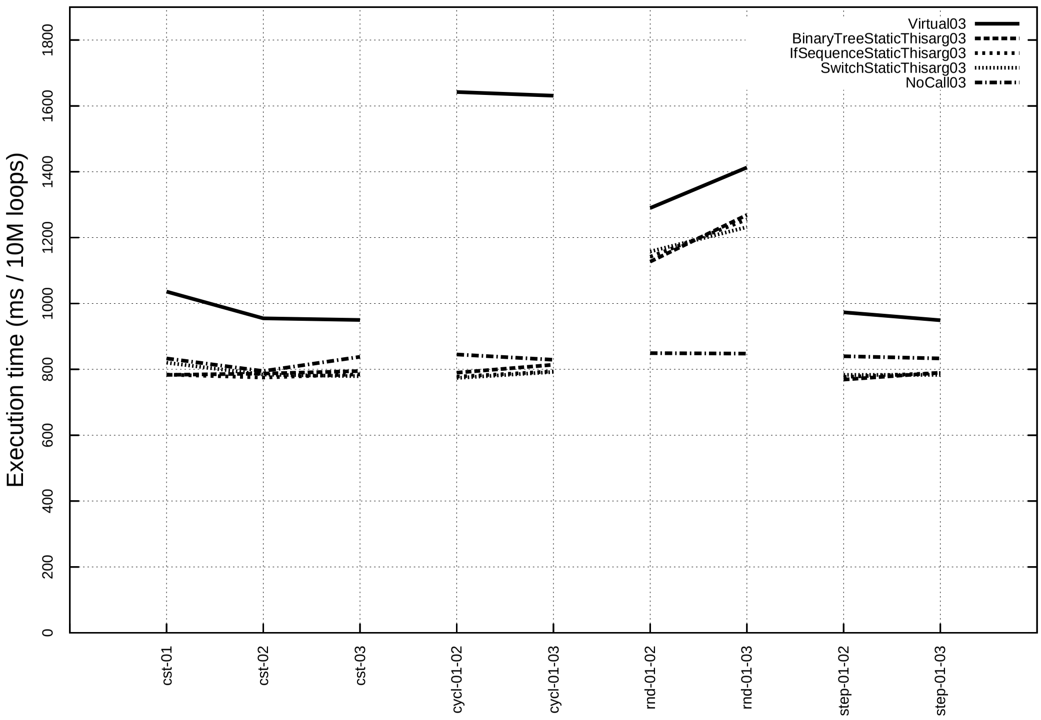


Figure 14: SUN HotSpot Server 1.3.1-b24 on a Celeron 466

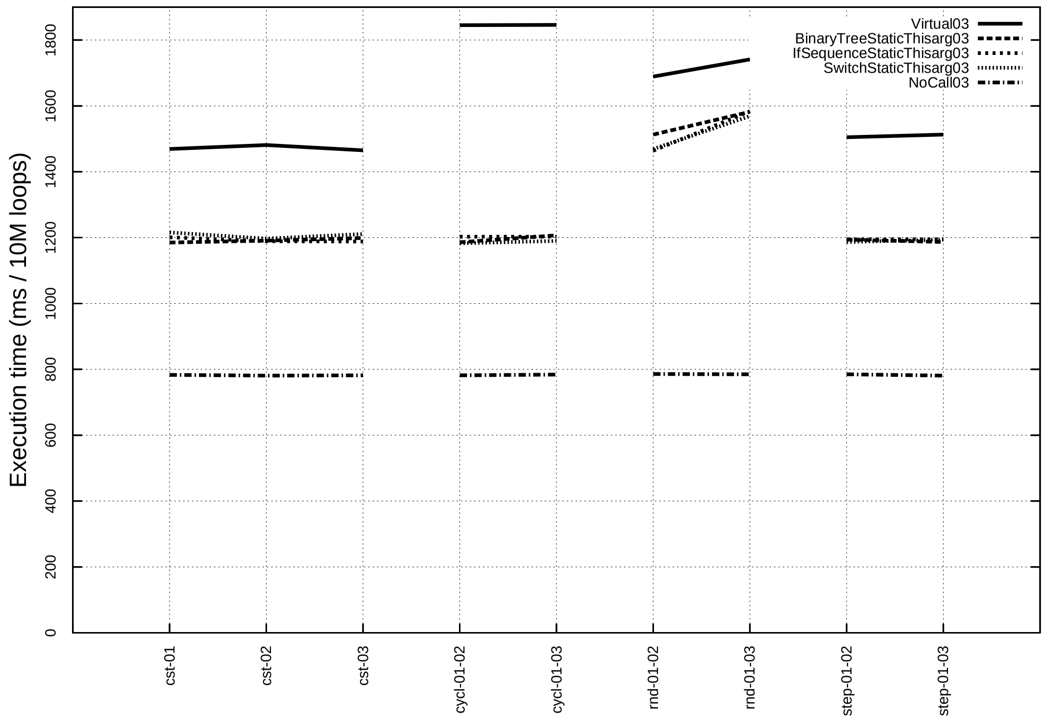
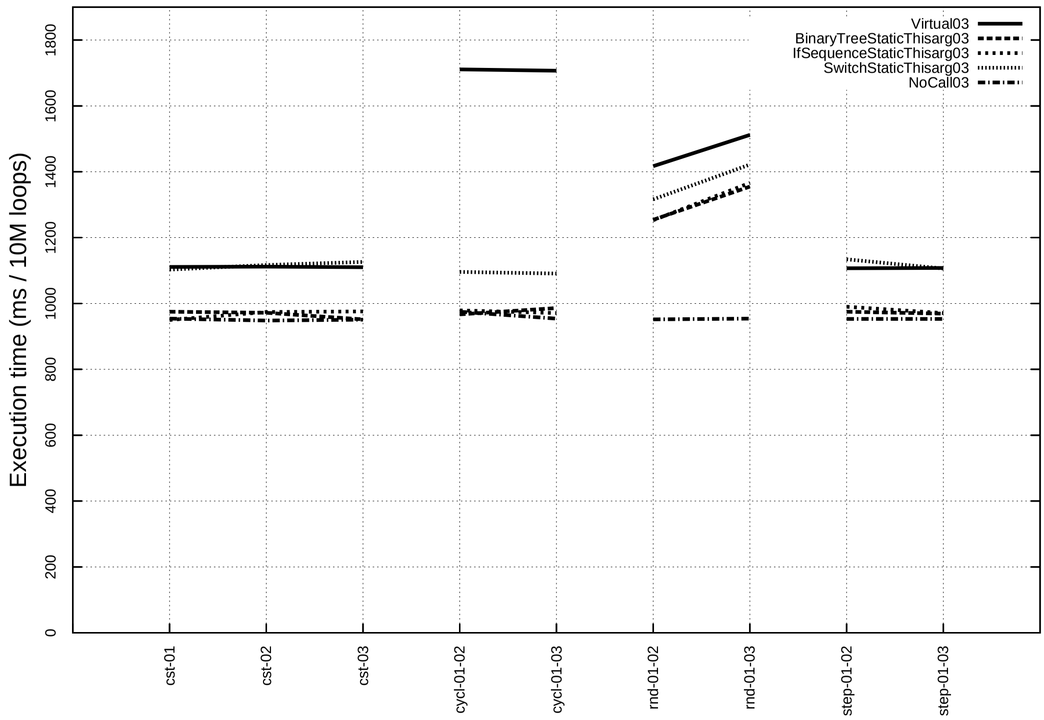


Figure 15: SUN HotSpot Client 1.3.1-b24 on a Celeron 466



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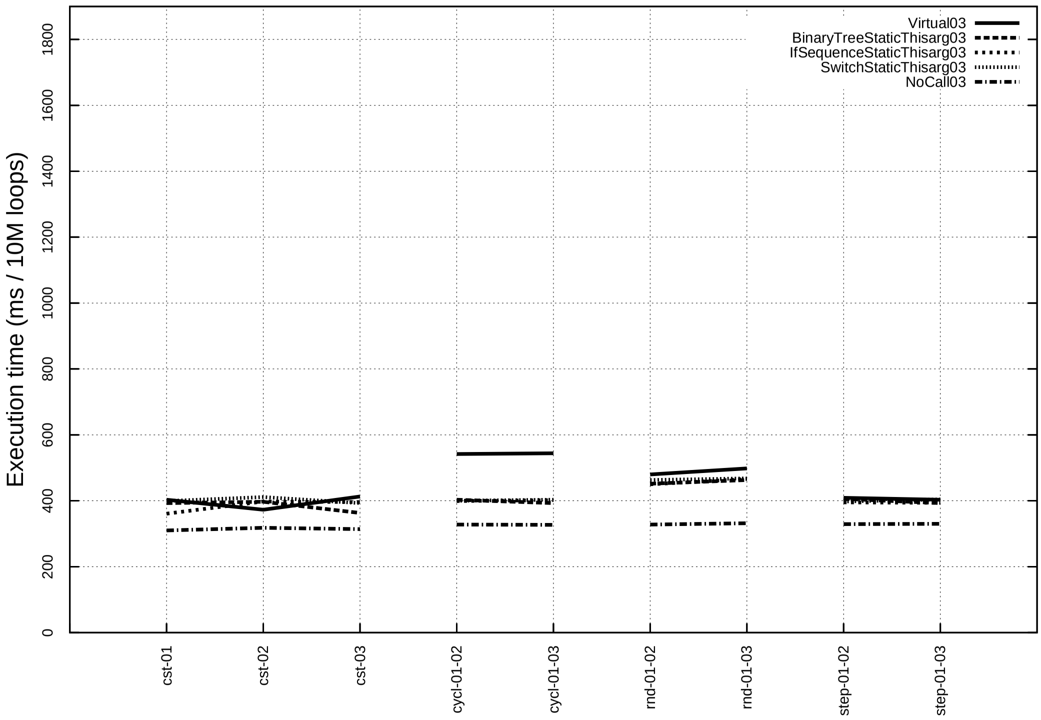


Figure 17: SUN HotSpot Server 1.3.1_01 on an Athlon 1400

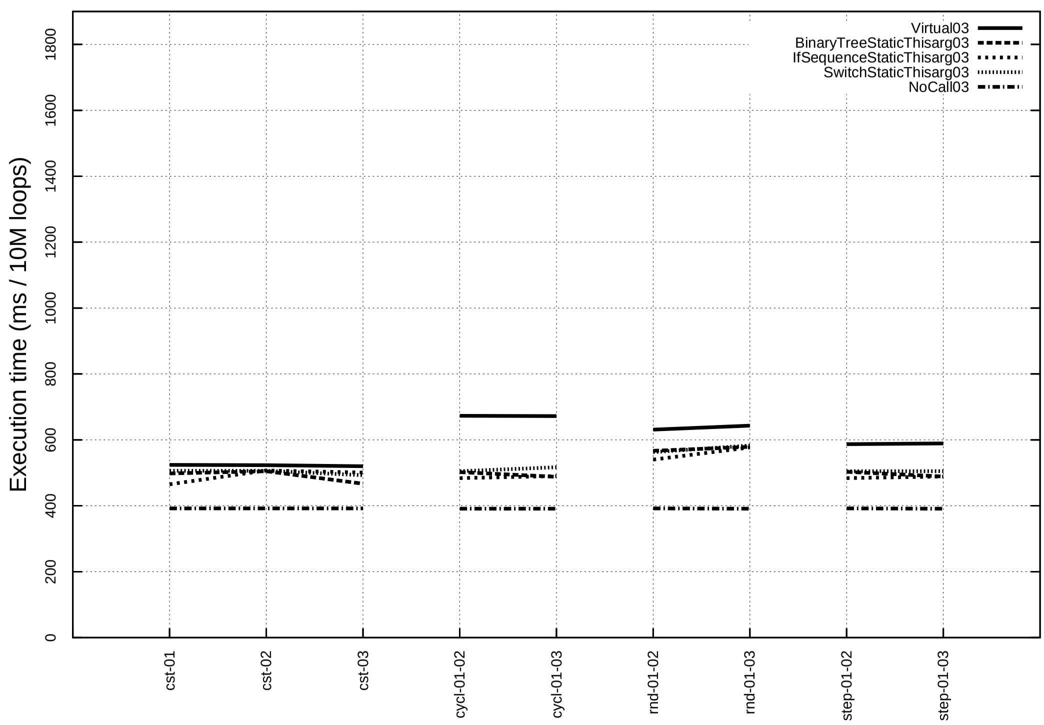


Figure 18: SUN HotSpot Client 1.3.1_01 on an Athlon 1400

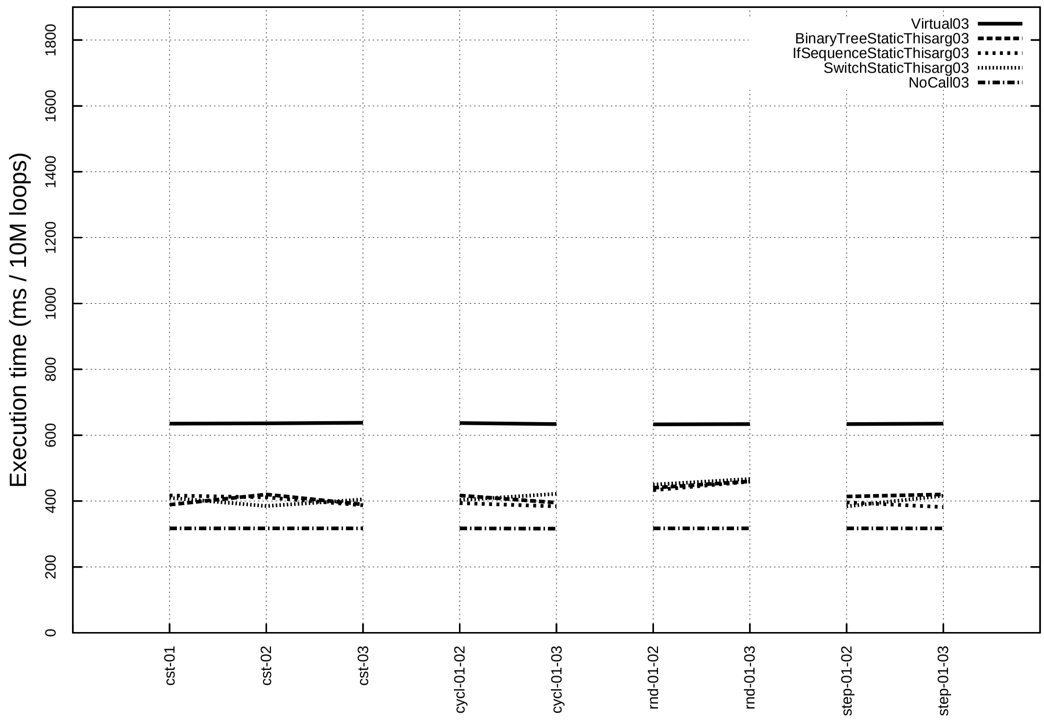


Figure 19: IBM JIT cx130-20010626 on an Athlon 1400

B All aggregated graphs for static size 7

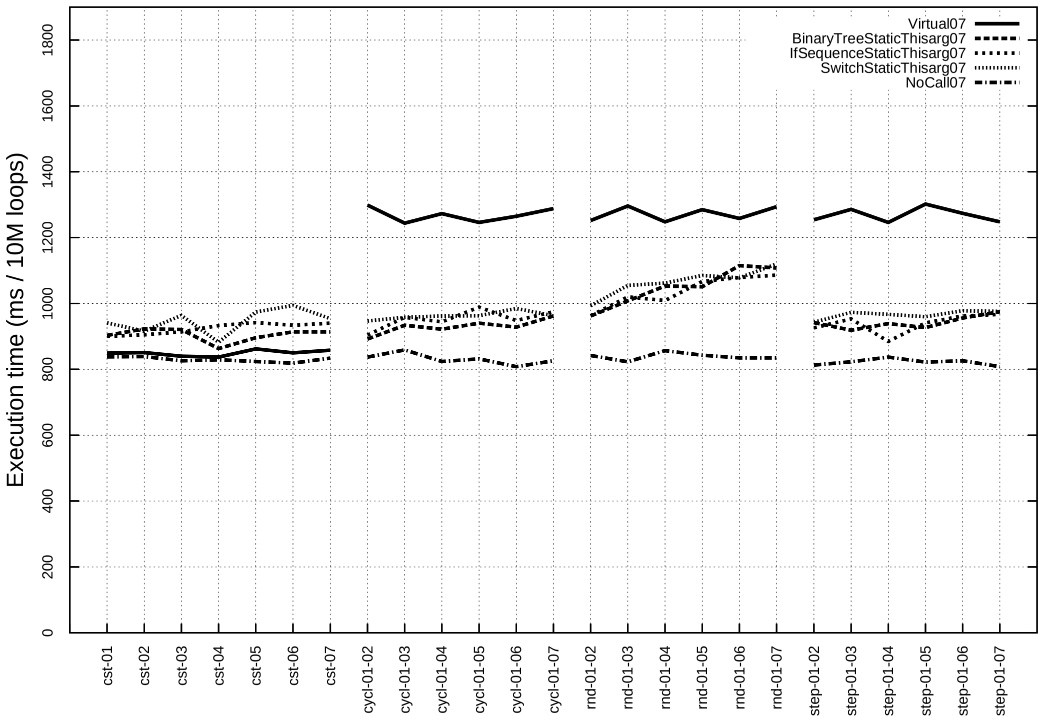
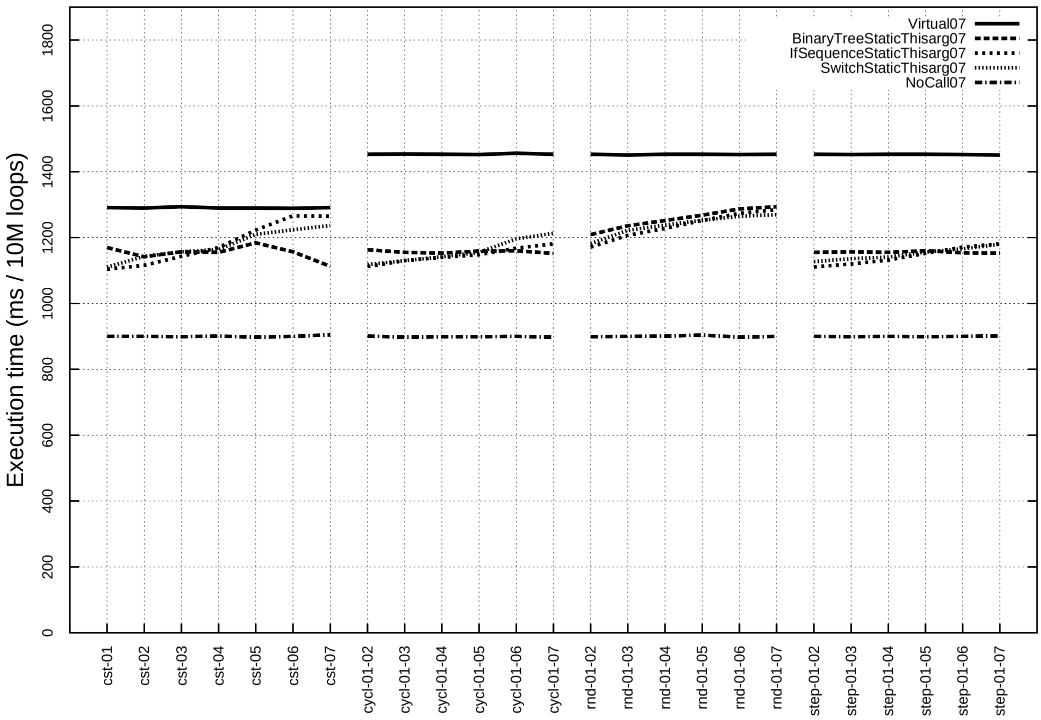


Figure 20: SUN HotSpot Server 1.3.1-b24 on an UltraSparc III 750



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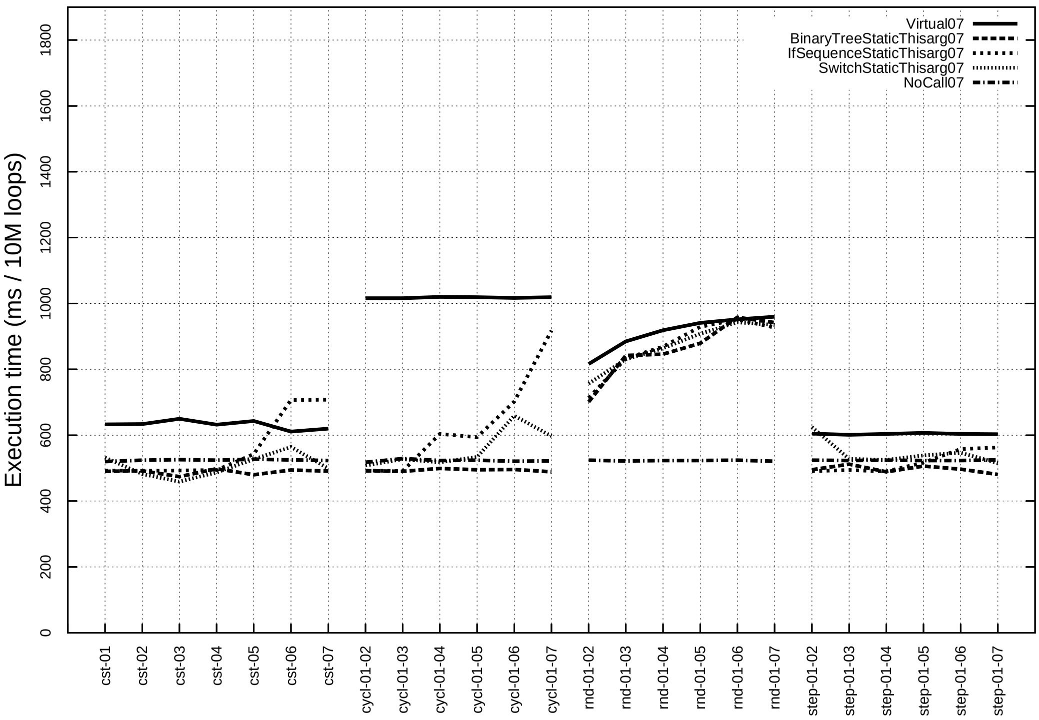

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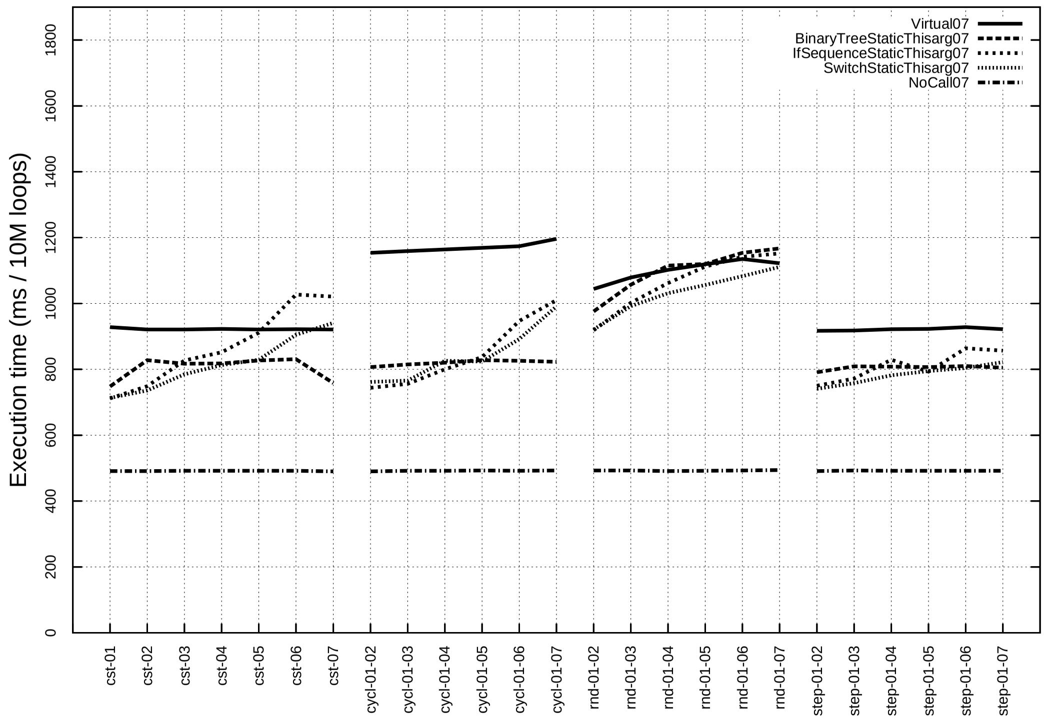

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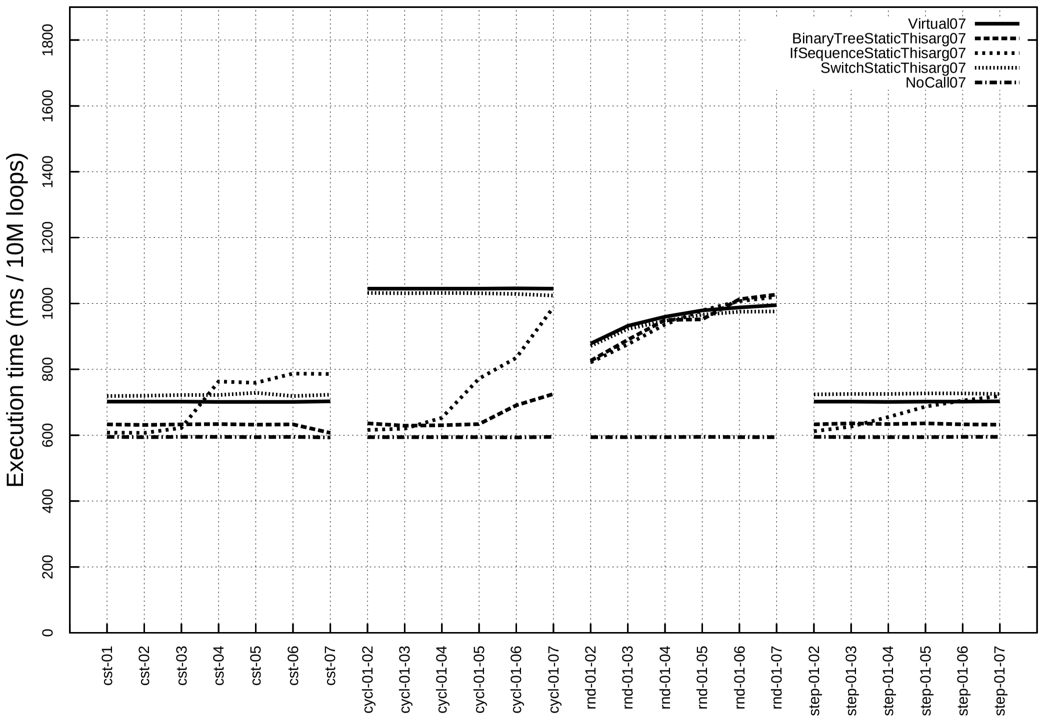

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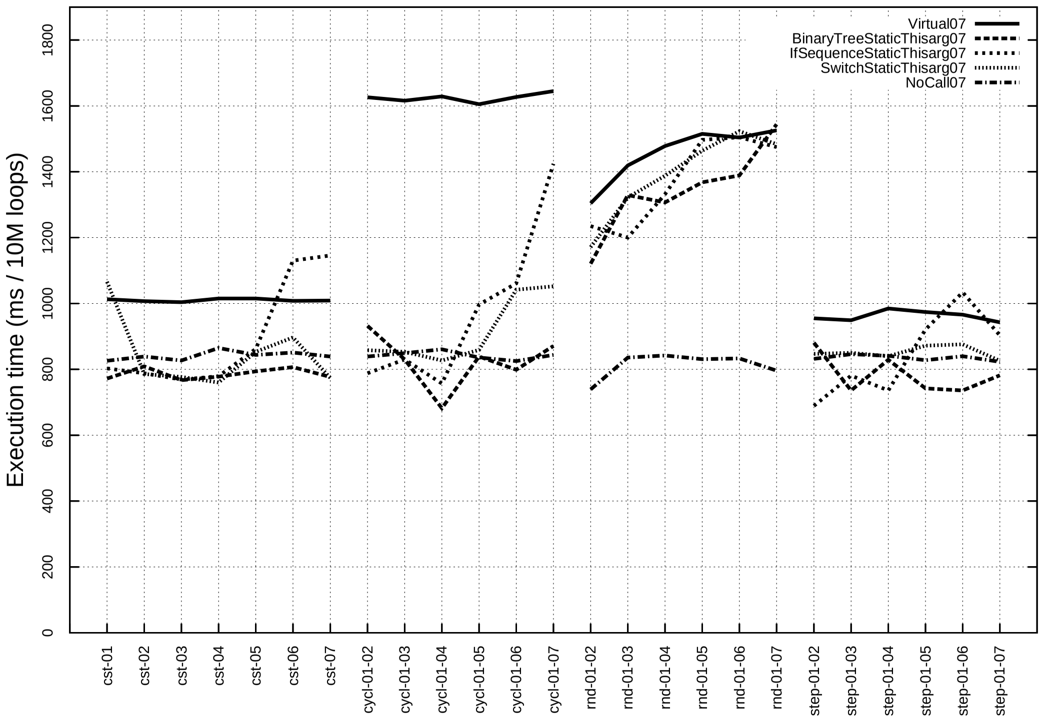
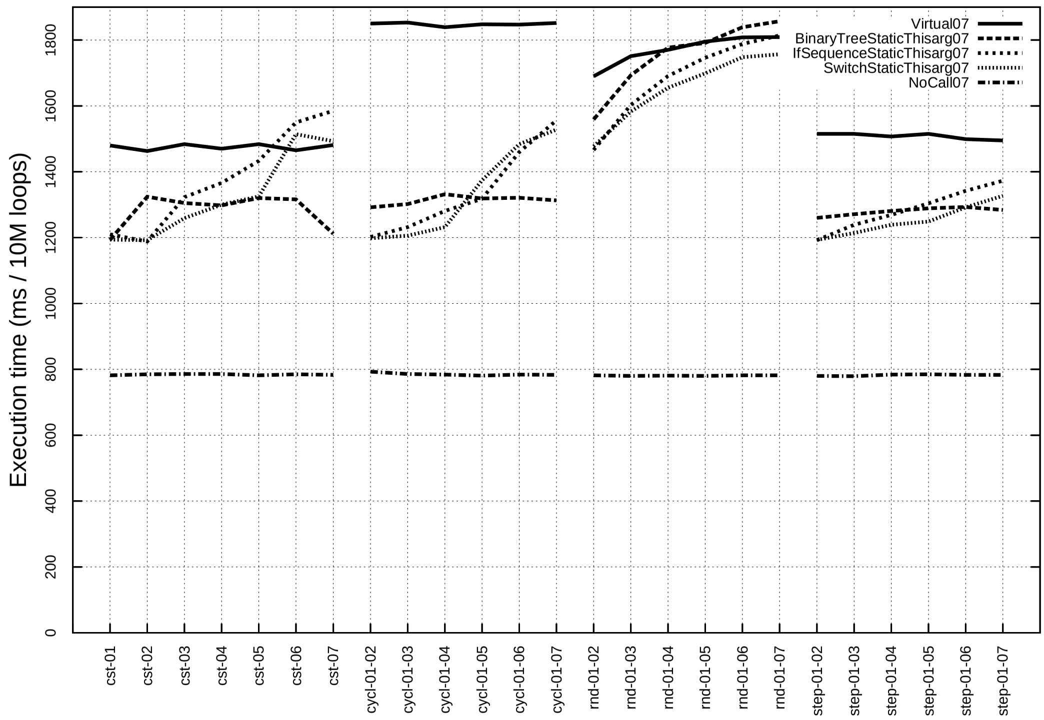


Figure 25: SUN HotSpot Server 1.3.1-b24 on a Celeron 466



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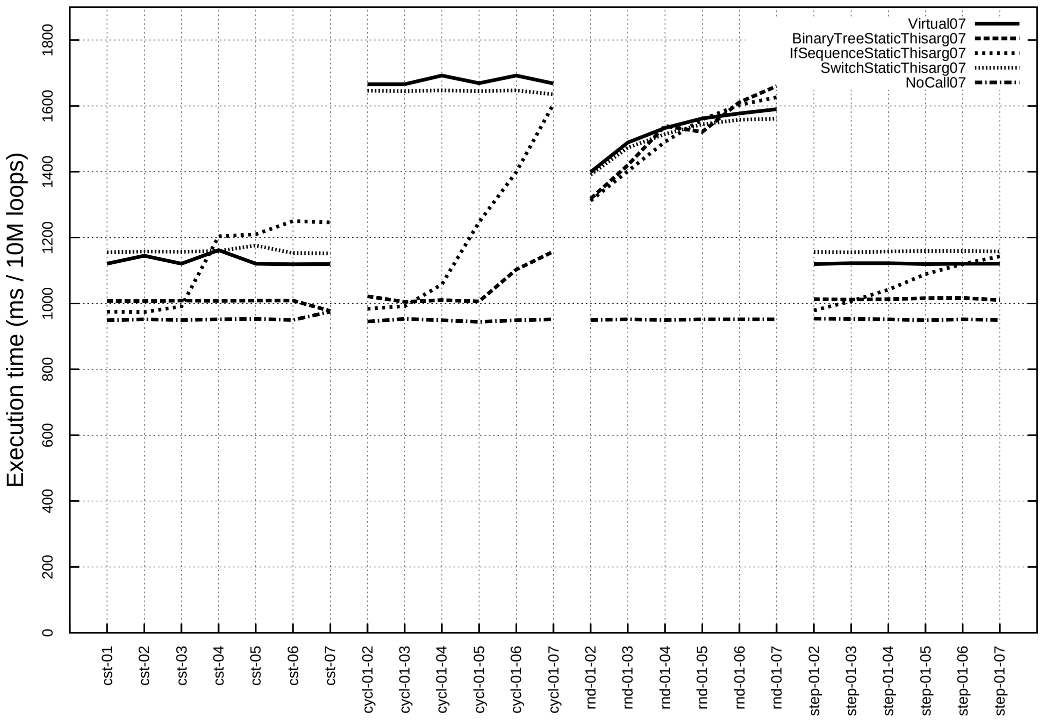

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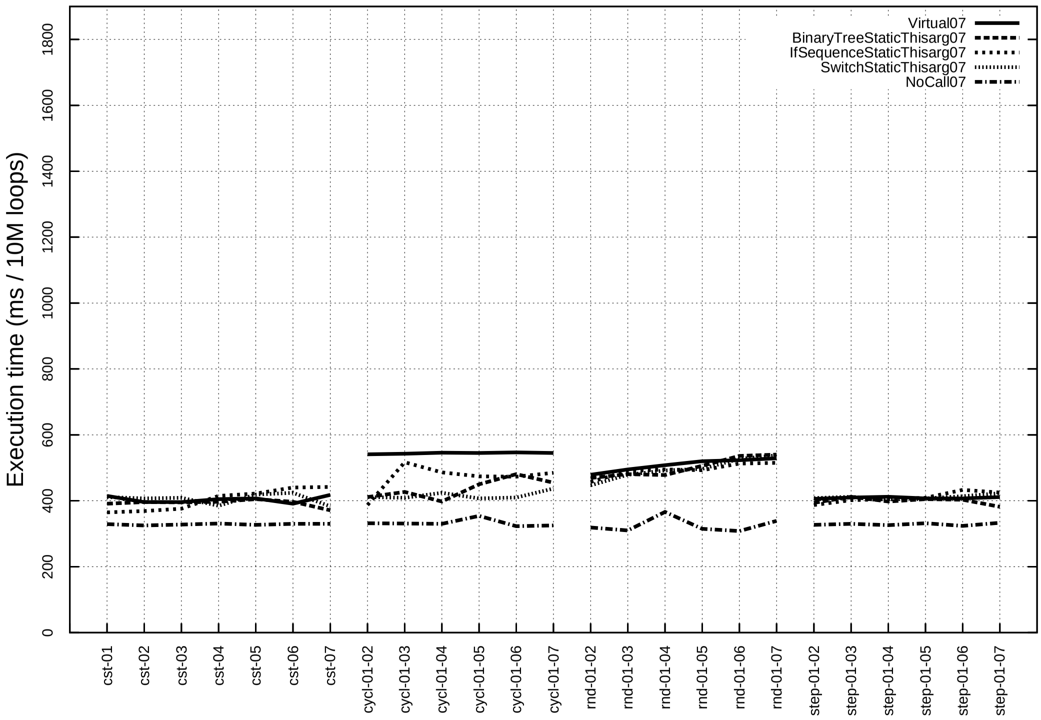
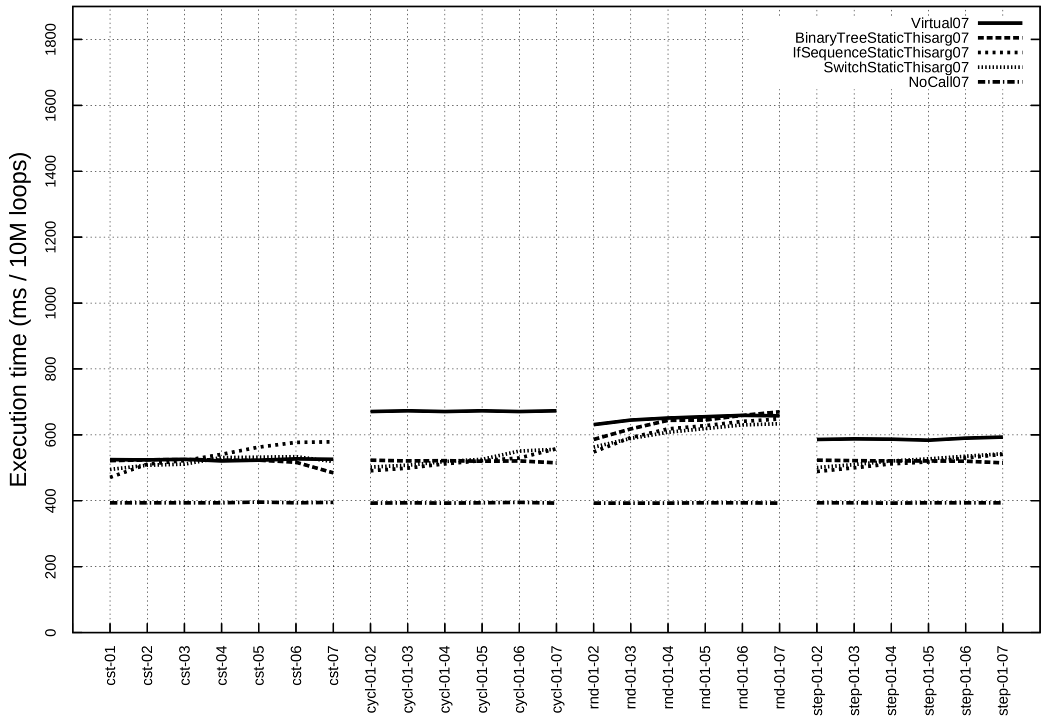


Figure 28: SUN HotSpot Server 1.3.1_01 on an Athlon 1400



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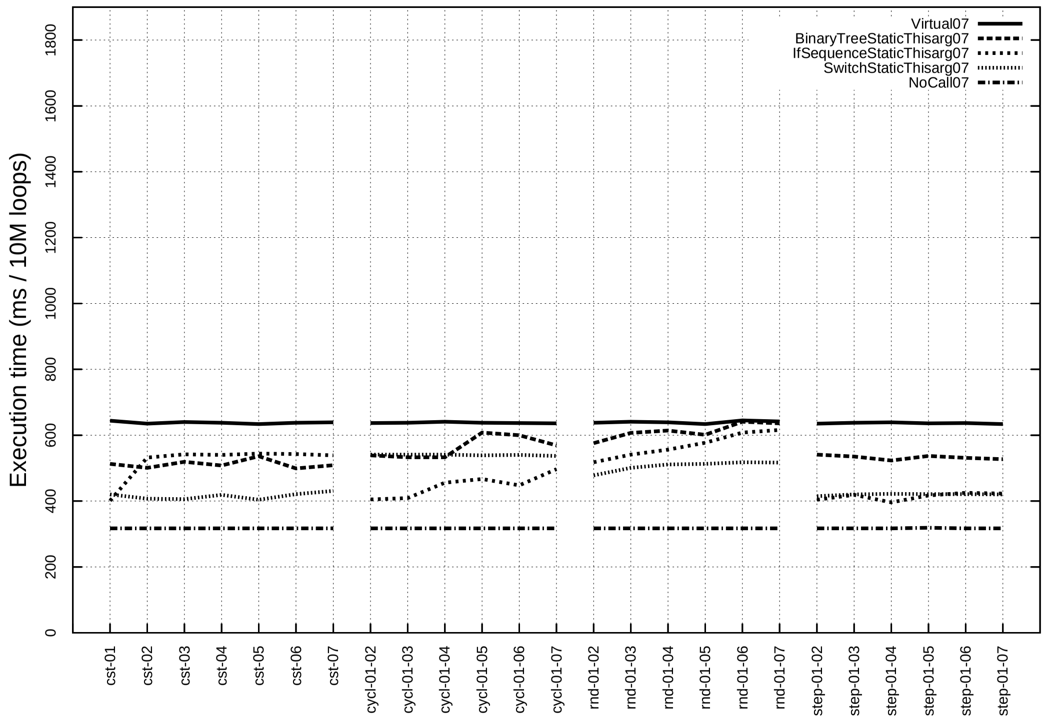


Figure 30: IBM JIT cx130-20010626 on an Athlon 1400

C All aggregated graphs for static size 20

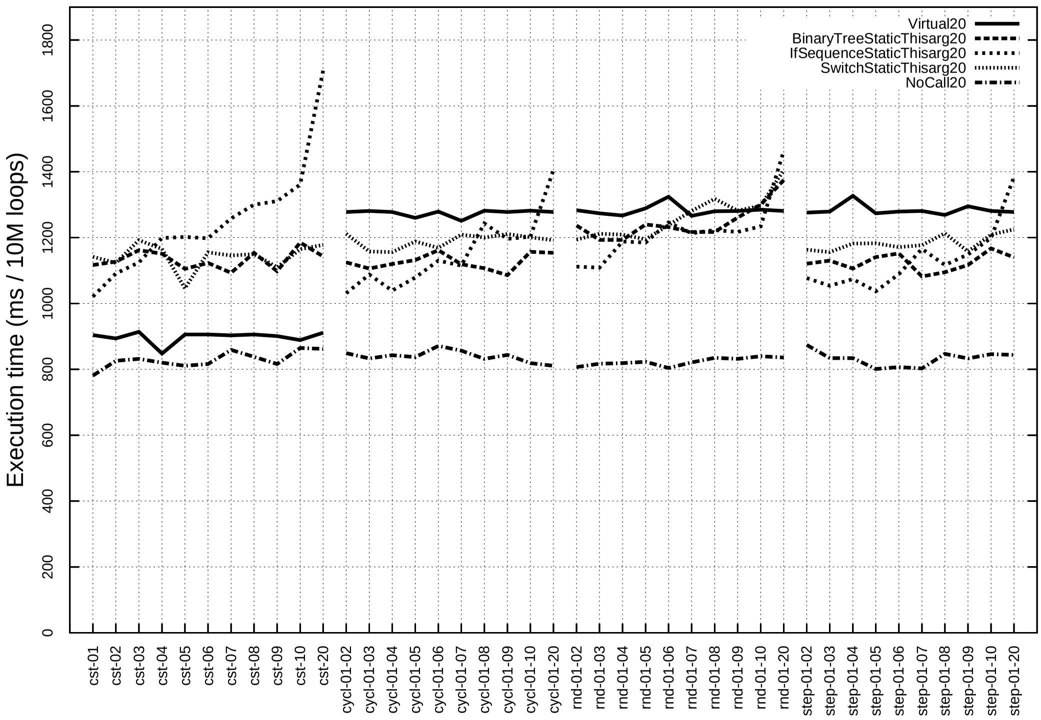
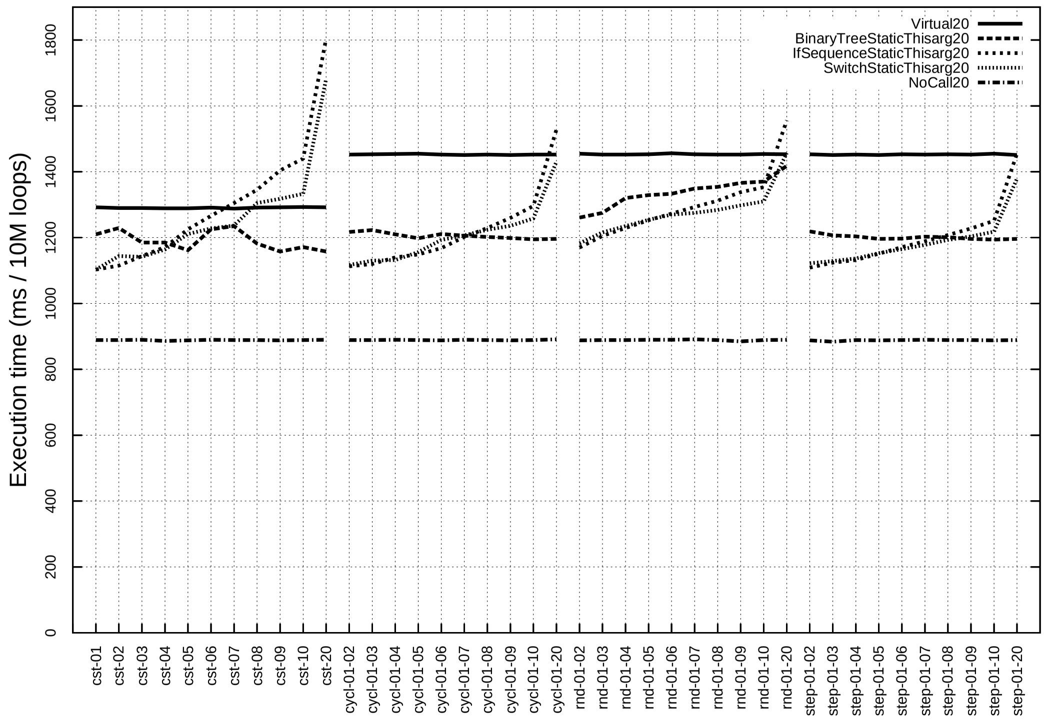


Figure 31: SUN HotSpot Server 1.3.1-b24 on an UltraSparc III 750



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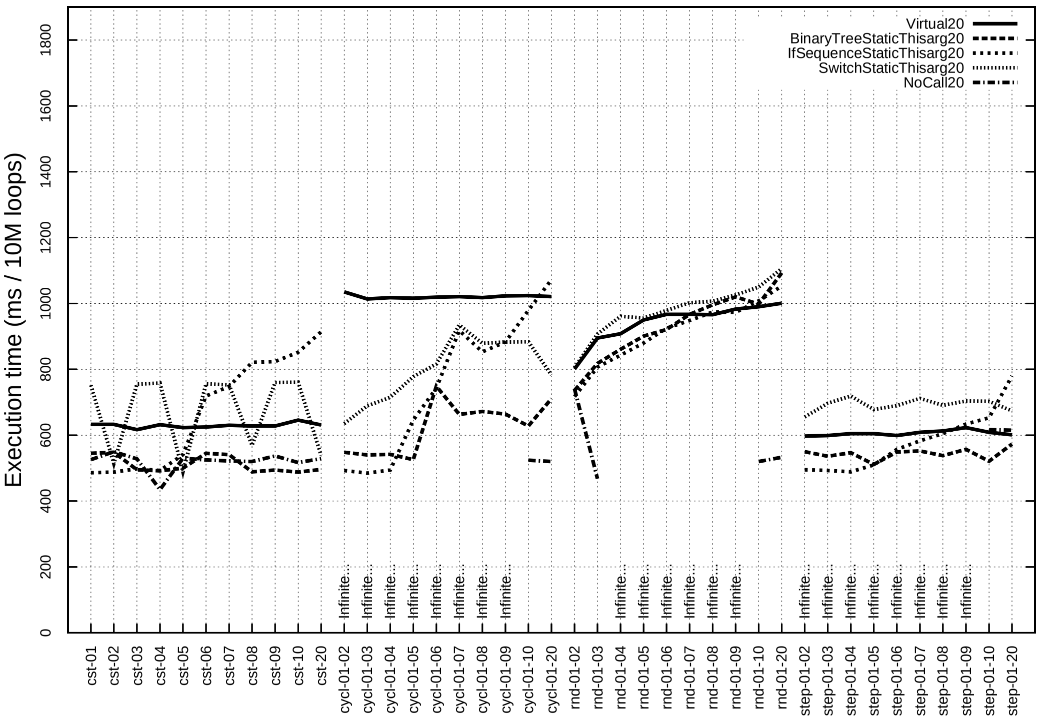
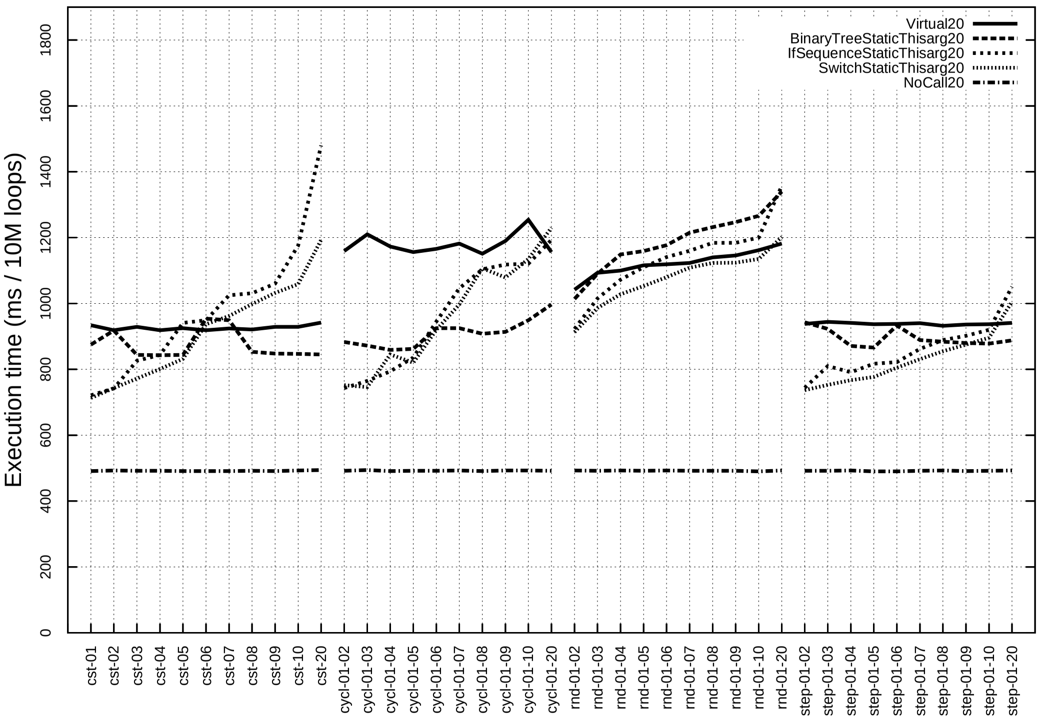


Figure 33: SUN HotSpot Server 1.3.1-b24 on a Dual Pentium III 733



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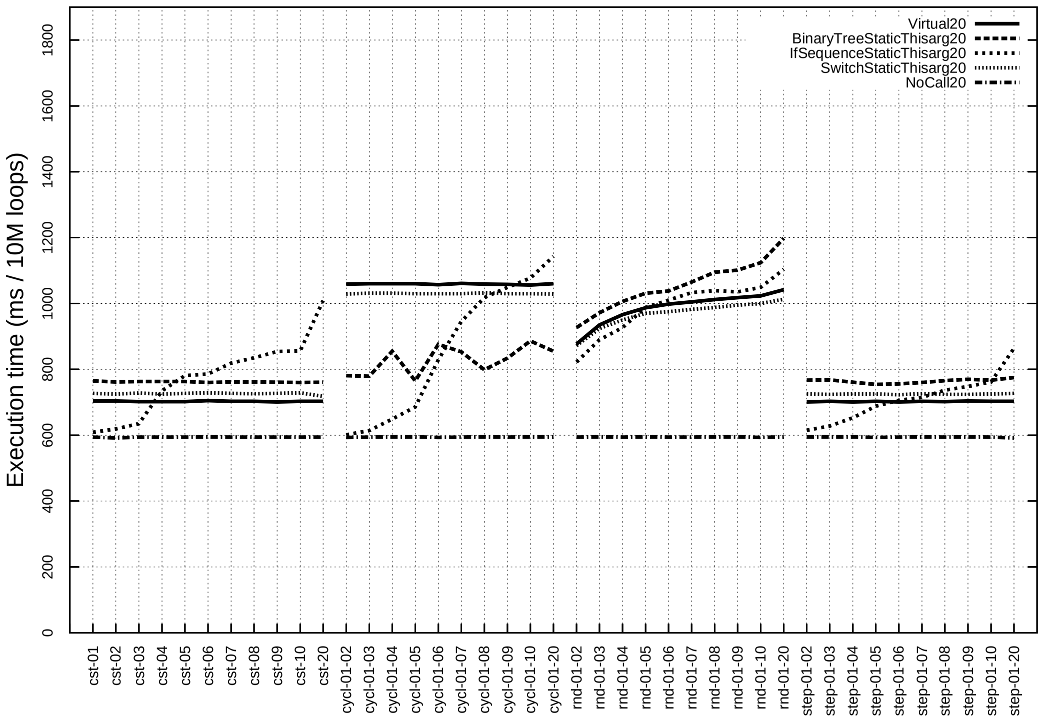

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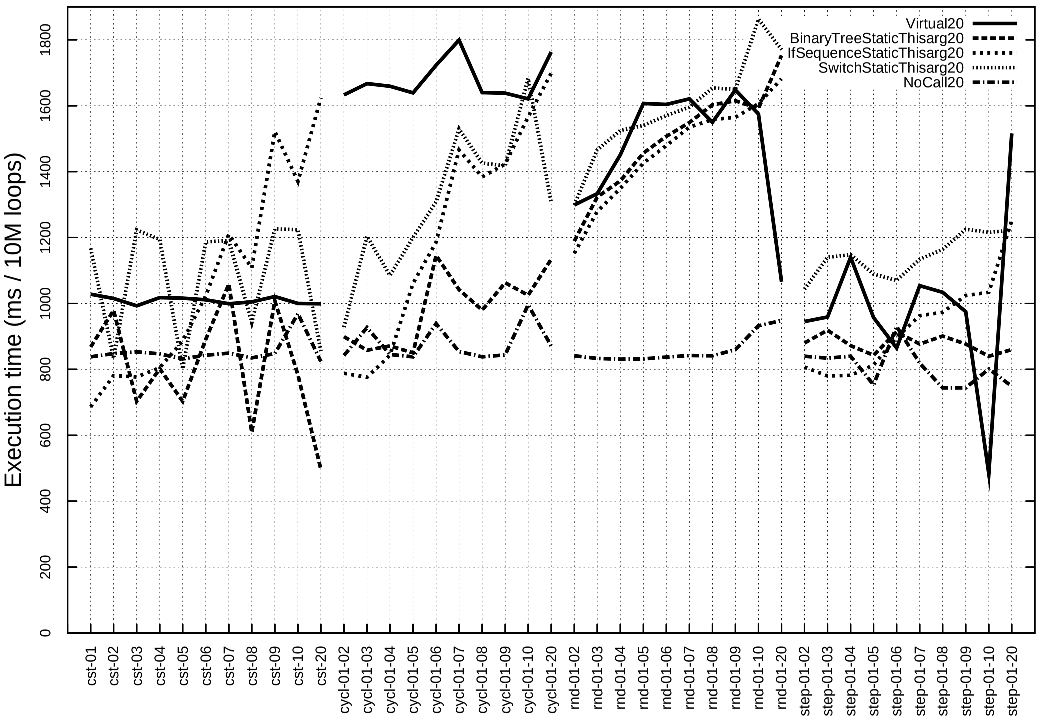
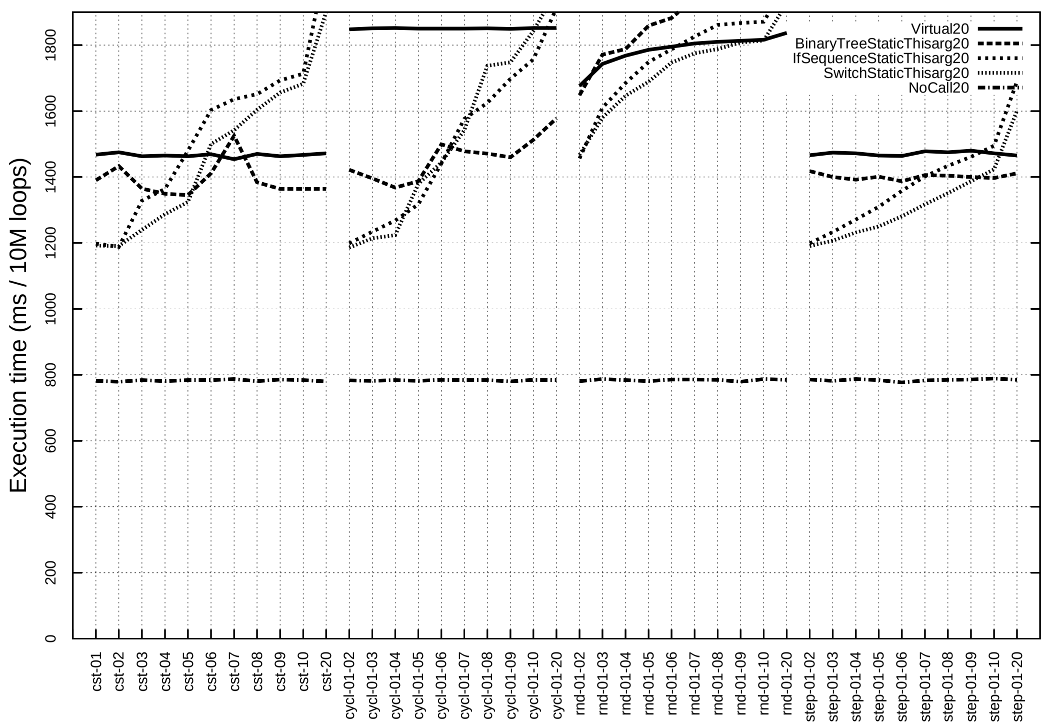


Figure 36: SUN HotSpot Server 1.3.1-b24 on a Celeron 466



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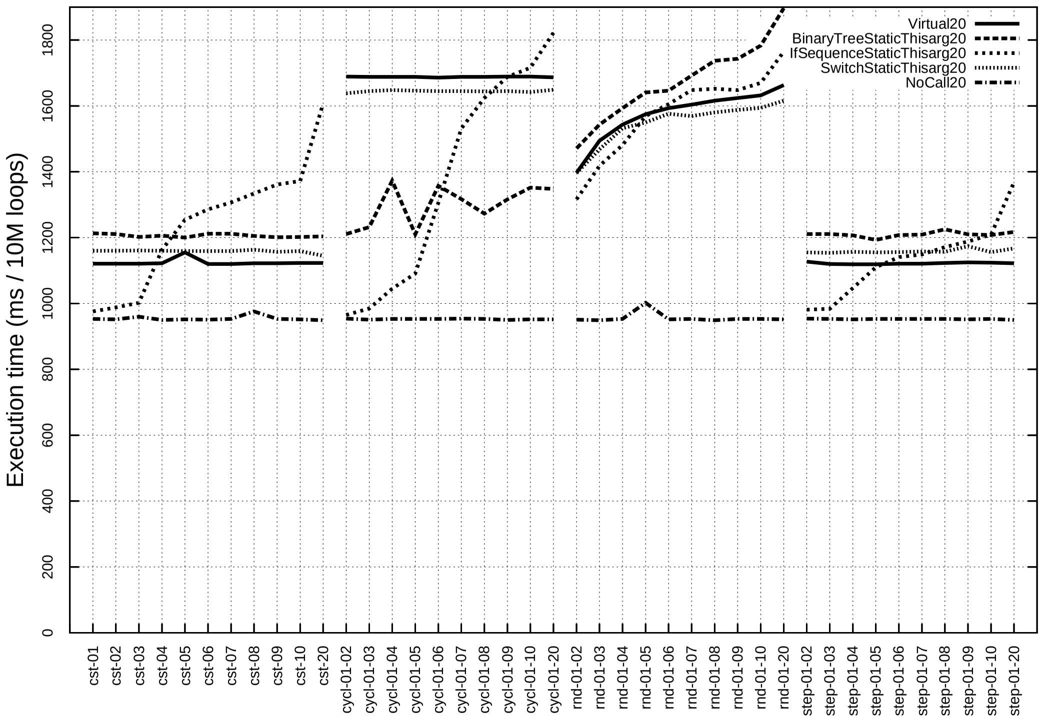

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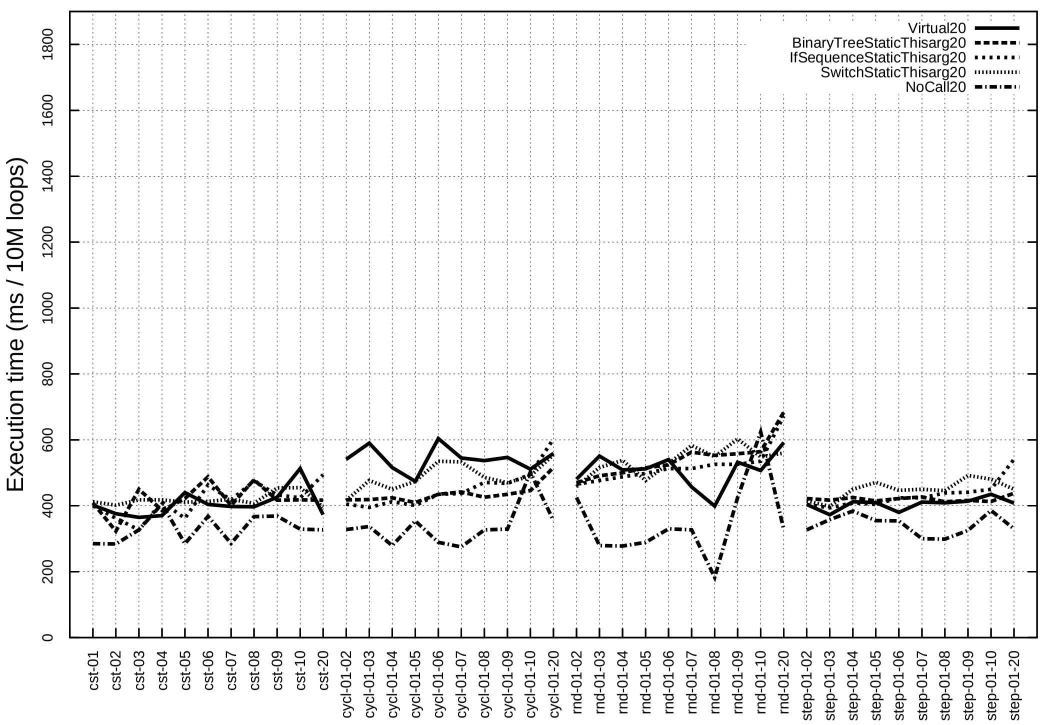

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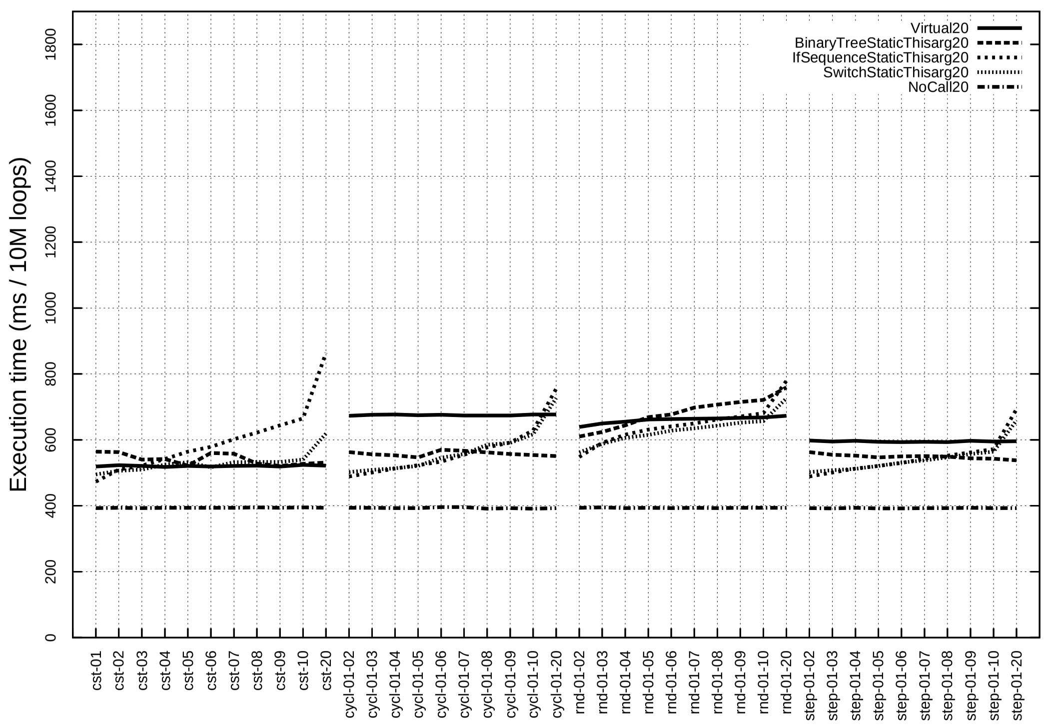

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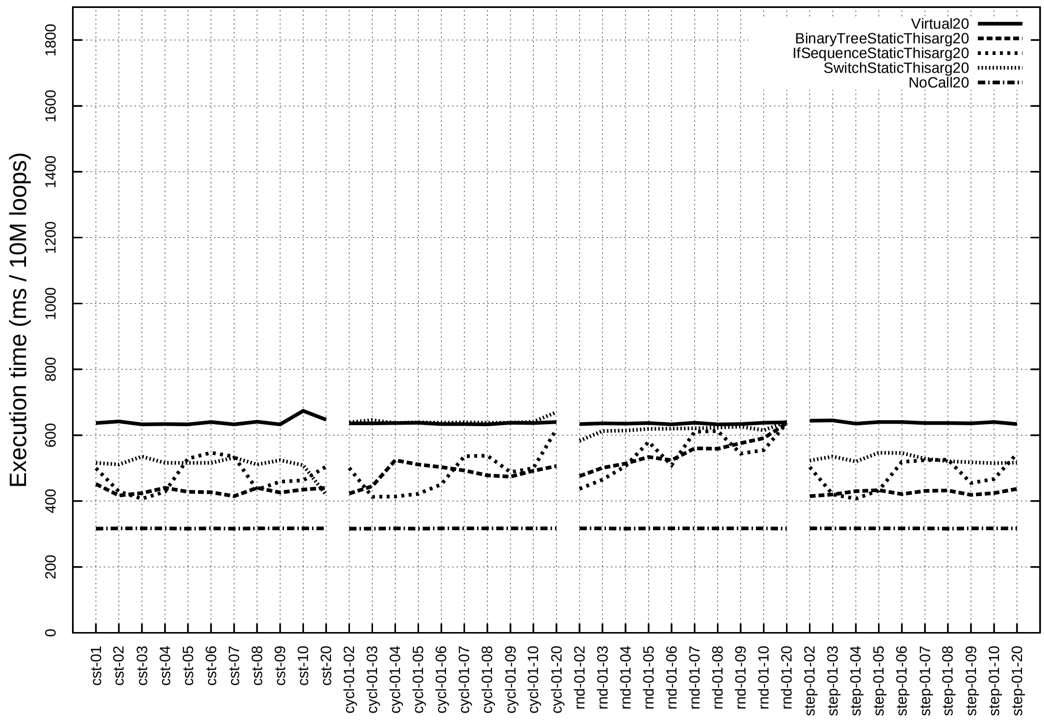

Figure 41: IBM JIT cx130-20010626 on an Athlon 1400

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